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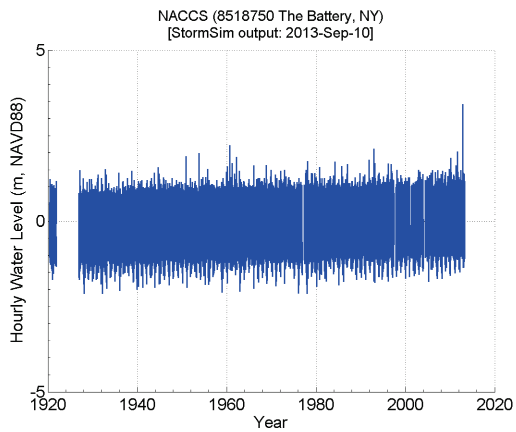
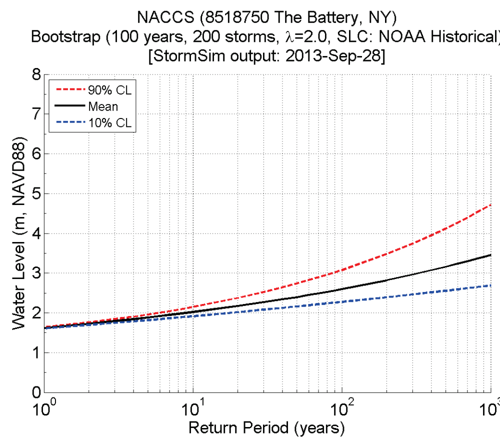
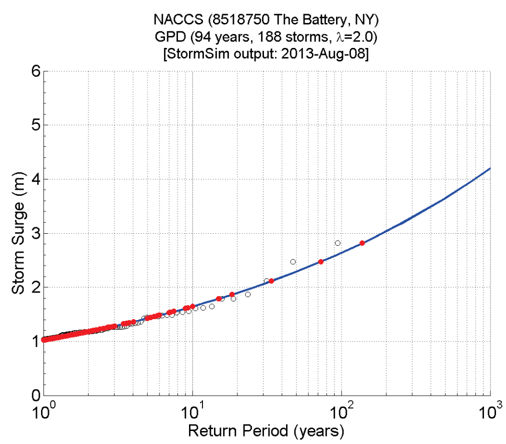
North Atlantic Coast Comprehensive Study Phase I: Statistical Analysis of Historical Extreme Water Levels with Sea Level Change

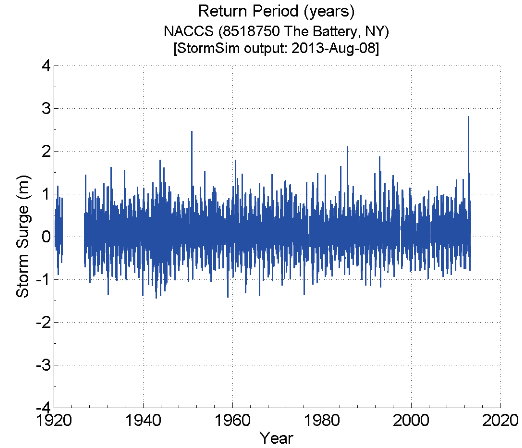
Norberto C. Nadal-Caraballo and Jeffrey A. Melby

September 2014









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Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180--6199

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City Crescent Building 10
South Howard Street
Baltimore, MD 21201

Abstract

The U.S. North Atlantic coast is subject to coastal flooding as a result of both severe extratropical storms (e.g., Nor'easters) and tropical cyclones (hurricanes). The North Atlantic Coast Comprehensive Study (NACCS) seeks to quantify existing and future forcing for use in assessing potential engineering projects that would reduce flooding risk and increase resiliency. The study encompasses the coastal region from Virginia to Maine.

The study summarized in this report is focused on providing interim statistical analysis of historical, regional, storm-induced water levels and forecasting future extreme water levels based on this analysis. The main objective of this effort is to obtain first-order estimates of storm-induced water level statistics at locations along the U.S. North Atlantic coast. Statistics were computed based solely on verified water level measurements provided by the National Oceanic and Atmospheric Administration's (NOAA) National Oceanic Service Center for Operational Oceanographic Products and Services, excluding any kind of high-resolution hydrodynamic modeling. Tropical and extratropical storms were treated as a single population. Water level distributions were computed using Monte Carlo methods with and without sea level change scenarios.

Extreme water levels as a function of return period were estimated for 23 gages spanning the northeast coast region. Continuous parametric distributions as well as empirical extremal distributions were computed as part of the statistical analysis. The extreme water level results based on historical data are shown to agree well with those computed by NOAA. Return period results for a range of sea level rise scenarios are presented as mean distributions as well as 10% and 90% confidence limits. Estimates of future extreme water levels due to sea level change represent the expected levels at the end of the 100-year horizon between 2015 and 2114.

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Preface

The study summarized in this report was conducted as a task within the North Atlantic Comprehensive Coastal Study funded by the USACE Baltimore District (NAB). Jason Engle (CESAJ-EN-WC) was the primary engineering point of contact. The study was funded by the USACE Headquarters through NAB and conducted at the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Vicksburg, MS, during the period April 2013–October 2013.

This report was prepared by Dr. Norberto C. Nadal-Caraballo and Dr. Jeffrey A. Melby, Harbors, Entrances, and Structures (HES) Branch, CHL.

Dr. Nadal-Caraballo and Dr. Melby were under the general supervision of Dr. Donald Ward, Acting Chief, HES Branch, and Dr. Jackie Pettway, Chief, Navigation Division. José Sánchez was Director, CHL, and Dr. Kevin Barry was Deputy Director, CHL.

COL Jeffrey R. Eckstein was Commander and Executive Director of ERDC. Dr. Jeffery P. Holland was Director.

Unit Conversion Factors

Most measurements and calculations for this study were done in SI units. The following table can be used to convert SI units to English customary units.

Multiply	By	To Obtain
meters	3.28084	feet
square meters	10.7639	square feet
cubic meters	35.3147	cubic feet
newtons	0.224808943	pounds (force)

1 Introduction

1.1 Problem

The North Atlantic Coast Comprehensive Study (NACCS) seeks to quantify existing and future forcing for use in assessing potential measures/projects that would reduce flood risk and increase resiliency. Potential future climate change must be included in the risk analyses. In the NACCS, rigorous regional statistical analyses and detailed high-fidelity numerical hydrodynamic modeling are being conducted for the northeast Atlantic coastal region from Virginia to Maine in order to quantify coastal storm wave, wind, and water level extremal statistics. These results will be available in 2014–2015. However, in the interim, future storm water level elevation extremes must be quantified for use in study screening analyses that will reduce risk from storm events and increase resiliency following storm events.

1.2 NACCS approach

Hereafter, the interim statistical analysis of historical water level measurements summarized in this study is referred to as Phase I of the NACCS. The ongoing regional statistical analysis and high-fidelity numerical hydrodynamic modeling are referred to as Phase II of the NACCS.

1.2.1 Phase I–Statistical analysis of historical extreme water levels with sea level change

The study summarized in Phase I is much lower fidelity than that of Phase II and is focused on analysis of measured historical storm-induced water levels for forecasting future statistical water levels. The main objective of this effort was to obtain first-order estimates of water level return periods at locations spanning the U.S. North Atlantic coast from Virginia to Maine.

Some of the limitations of this study include very sparse spatial resolution, short record lengths at particular locations, and measurement gaps during some of the most extreme events due to gage failure. Statistics were computed based solely on verified water level measurements provided by National Oceanic and Atmospheric Administration's (NOAA) National Oceanic Service (NOS) Center for Operational Oceanographic Products and

Services (CO-OPS), excluding any kind of high-resolution hydrodynamic modeling. Also, tropical and extratropical storms were treated as a single population. Over much of the northeast Atlantic coastline, hurricane landfalls are sparse in the modern historical record. Thus, in terms of hurricane responses recorded by water level gages, the hurricane population is severely underrepresented, resulting in significant statistical uncertainty, mainly for return periods near and greater than 100 years (yr).

Note: For the purpose of project risk assessment and resiliency analysis, the results from this study (Phase I) are considered interim and will be superseded by Phase II results.

The general methodology for this Phase I study is outlined in Chapter 2, and the detailed methodology is described in Chapter 3. The results are summarized in Chapter 4 and in the Appendices.

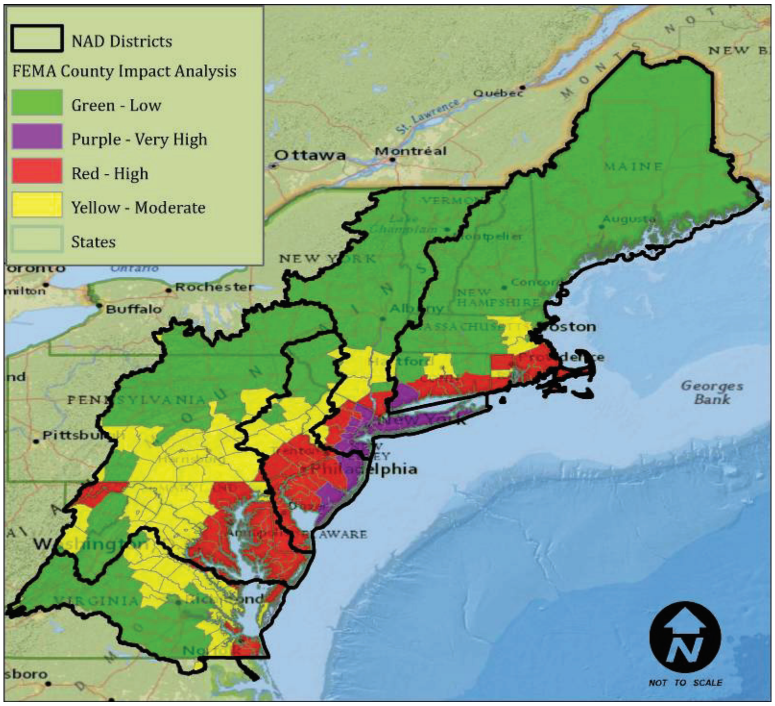
1.2.2 Phase II–Combined joint probability analysis and high-fidelity modeling of tropical and extratropical storms

Within the NACCS, there are tasks focused on detailed high-fidelity modeling of most processes. The wave and water level task includes quantifying the statistical characteristics of regional storm characteristics, constructing one or more regional joint probability models (JPM) of storm characteristics, efficiently sampling from this JPM to generate synthetic storms that span the parameter and probability space, and then modeling the processes of these storms from basin scale down to local scale. The high-fidelity response includes storm wind and atmospheric pressure, wave, and surge along with tides and sea level change (SLC).

1.3 Study area

Coastal flooding is primarily caused by rainfall, storm surge, and waves. For the northeastern U.S. Atlantic coastline, tides can have a significant influence on the degree of flooding. For the region from Virginia to Maine, both tropical cyclones (hurricanes) and extratropical storms (e.g., Nor'easters) have caused significant coastal flooding. Portions of the region are low lying and sinking as a result of land subsidence. Combined with global SLC from ocean warming and melting ice, relative SLC is an important issue for much of the study region. A regional map showing the area under consideration is given in Figure 1.

Figure 1. Regional map of area considered in this report



Flood and wind damage from annual coastal storms continues to cause dramatic negative impacts to the national economy with direct cost of over $400 billion for the top seven hurricanes (Blake et al. 2011)[1] . Six of the top seven most damaging storms have occurred since 2004. Over 52% of the U.S. population lives in coastal watershed counties, and the coastal population is expected to increase 10% in the years preceding 2020 (Burkett et al. 2012). SLC and increasing storminess are exacerbating the vulnerability of coastal communities. In 2012, Hurricane Sandy accounted for more than 60 deaths, 600,000 damaged homes, and 8.5 million customers left without electricity, totaling over $65 billion in damages in New York, New Jersey, and Connecticut alone (Pirani and Tolkoff 2014).

1.4 SLC scenarios

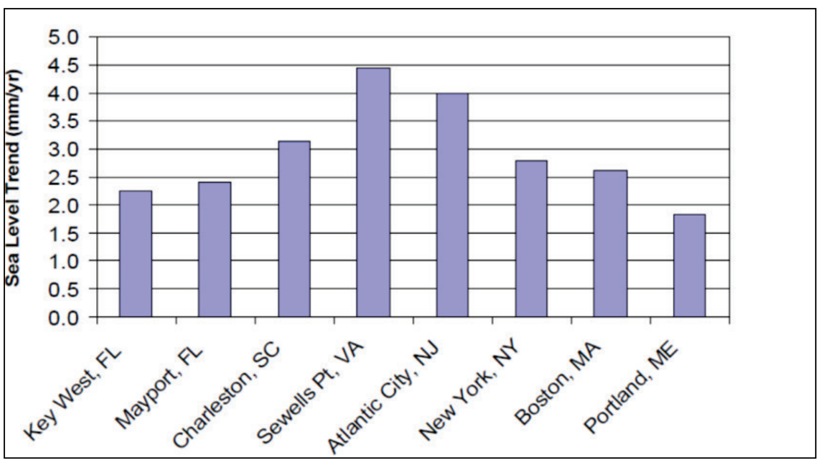
As described in Headquarters, U.S. Army Corps of Engineers (2011), global sea levels are generally rising as a result of regional water body thermal expansion. The Intergovernmental Panel on Climate Change (IPCC) AR4 (IPCC 2007) estimate of eustatic, or global mean sea level change (GSLC), is 3.1 millimeters/yr (mm/yr) for the period 1993–2003 and 1.7 mm/yr for the period 1961–2003. Conversely, the relative sea level change (RSLC) is

[1] The total costs were verified with individual storm Wikipedia sites and updated through 2012.

the SLC that includes both global SLC and local land subsidence or uplift/rebound as well as other local water level influences from currents and local sea warming or cooling. This local SLC is what is measured by a water level gage. Local subsidence in populated areas as a result of ground water and/or oil and gas extraction exacerbates SLC while uplift due to tectonic plate movement or postglacial rebound often counteracts local SLC. The far northeast coast exhibits significant postglacial rebound so the SLC is lower than in the central northeast region where land subsidence is a dominant process (Boon et al. 2010).

As described by Boon et al. (2010), complicating SLC, local long term changes in water levels result from spatial and temporal variations in water density, basin-scale currents, and other impacts. A regional summary of SLC from Zervas (2009) is shown in Figure 2.

Figure 2. Regional summary of SLC from NOAA (Zervas 2009) . Record lengths vary between 1928–2006 at Mayport, FL, and 1856–2006 at New York.



USACE guidance for GSLC (Headquarters, U.S. Army Corps of Engineers 2011) recommends using modified versions of the National Research Council (National Research Council 1987) forecast curves. GSLC is computed using the equation

$$E(t_2) - E(t_1) = 0.0017(t_2 - t_1) + b(t_2^2 - t_1^2) \qquad (1)$$

where t_2-t_1 is the time from 1992, and $E(t_2)$-$E(t_1)$ is the difference in water levels. When the curves' base year is other than 1992, the variables t_2 and t_1 need to be adjusted accordingly. For example, for a 100 yr life cycle with base year 2014, t_2 and t_1 should be computed as follows:

$$t_1 = 2014 - 1992 = 22$$

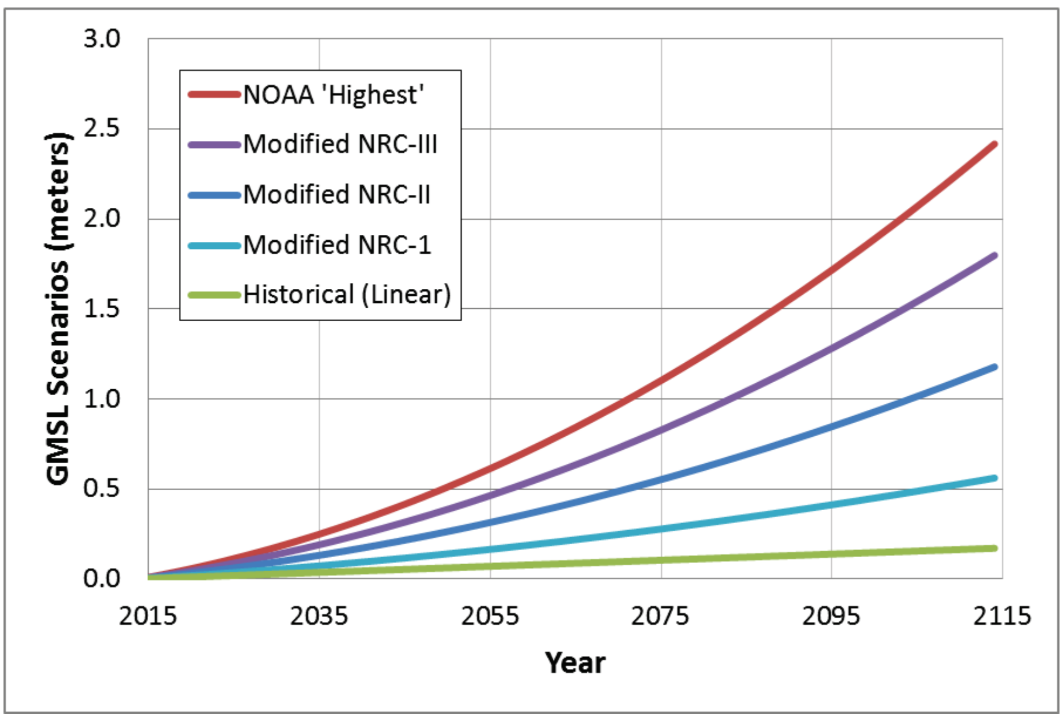
$$t_2 = (2015 - 1992 = 23), \ldots, (2114 - 1992 = 122)$$

USACE (Headquarters, U.S. Army Corps of Engineers 2011) recommends modifying the b coefficient on the nonlinear term of Equation (1) in order to compute various potential GSLC scenarios. In this report, five deterministic SLC scenarios were computed, as well as a stationary scenario (base case):

- Scenario 1–Base case/No SLC
- Scenario 2–Historical mean (USACE Low)
- Scenario 3–Modified NRC-I rate (USACE Intermediate)
- Scenario 4–Modified NRC-II rate
- Scenario 5–Modified NRC-III rate (USACE High)
- Scenario 6–NOAA Highest rate

The deterministic GSLC Scenarios (2 though 6) used in this study are shown in Figure 3.

Figure 3. GSLC Scenarios used in this study.



For the historical mean GSLC (Scenario 2), a rate of +1.7 mm/yr was used (Headquarters, U.S. Army Corps of Engineers 2011).

The modified values of the *b* coefficients corresponding to the Scenarios 3 through 6 are summarized in Table 1.

Table 1. Coefficients for GSLC curves.

ID	SLC Scenario	Coefficient *b* from Eq. (1)
3	Modified NRC-I	2.71E-05 (USACE 2011)
4	Modified NRC-II	7.00E-05 (USACE 2011)
5	Modified NRC-III	1.13E-04 (USACE 2011)
6	NOAA Highest	1.56E-04 (NOAA 2012)

To account for local vertical mean sea level trends that are different from the eustatic mean sea level trend of 1.7 mm/yr, the coefficient on the linear term of Equation (1) is adjusted by superimposing the GSLC rate with the local SLC rate. For each gage, the local mean sea level trend was computed, and Equation 1 was modified to compute RSLC.

2 Methodology

2.1 Summary

All statistical analyses detailed in this report were conducted by the authors using the StormSim software, also developed by the authors. StormSim is an extremal statistical analysis and storm simulation software system. In its present form, StormSim is an integrated framework of Matlab scripts developed for statistical analysis of coastal storm parameters and coastal storm response. The routines within StormSim are generalized and have been used on a number of previous studies (Nadal-Caraballo et al. 2012; Melby et al. 2012). Individual StormSim routines for analyzing time series, computing extremal distributions, and plotting results have been distributed for various Federal Emergency Management Agency (FEMA) Risk Mapping, Assessment and Planning (Risk MAP) studies. However, currently, the system is not generally distributable because it is still in a state of rapid development and expansion.

The study methodology followed a three-stage process. The first stage is the extremal analysis of historical water levels. Here, historical hourly water levels are complemented by NOAA's monthly maxima records. Therefore, the extreme distributions developed at this stage are considered the *true* distributions. In the second stage of this study, a Monte Carlo Life-Cycle (MCLC) simulation is performed to account for the SLC scenarios discussed in Section 1 of this report. Residuals (storm surges) estimated from hourly records and astronomical tides are randomly sampled and linearly superimposed to time-dependant SLC contributions to generate synthetic extreme water level responses (storm tides). Since the MCLC simulation performed in this study is only viable using hourly data, it excludes extreme events only captured in the monthly maxima records. While the extreme distributions developed at this stage might be inaccurate, the purpose of the MCLC simulation and of the distributions developed in this process is to capture how future extreme water levels are affected by potential SLC scenarios and inherent uncertainties. Transformation coefficients are needed to scale the true extreme distributions to possible future SLC scenarios. For the third stage, sets of transformation coefficients are computed from the stage 2 MCLC results and used to properly scale the extreme water level probability distribution from stage 1 for each of the SLC scenarios assessed in this study.

2.2 Extremal analysis of historical water levels

The methodology for this stage is summarized as follows:

1. Select water level gages based on location and record length. Collect all available hourly and monthly maxima water level data for each gage from NOAA and verify data integrity.
2. Detrend both monthly maxima and hourly data series using a linear regression with zero-crossing at year 1992.5, which is the midpoint of the National Tidal Datum Epoch (NTDE) of 1983–2001.
3. Adjust the detrended series to present-day conditions by adding the difference between 1983–2001 mean sea level (MSL) and present-day MSL.
4. Use peaks-over-threshold (POT) technique to sample a given number of events per year (λ) from both monthly maxima and hourly data series. The products from this task are partial duration series of extreme water levels (or storm tides).
5. Compare POT results from both monthly maxima and hourly records to eliminate duplicate events. Merge and rank order POT water levels from both sets and retain only enough events to match the required λ.
6. Use the Generalized Pareto Distribution (GPD) and the Maximum Likelihood Method (MLM) to fit the extreme water level empirical data to parametric distributions and compute return levels.
7. Use bootstrapping (a particular case of Monte Carlo methods) to randomly sample from the GPD to simulate a 100 yr lifecycle and extend the record length (RL) of all of gages to 100 yr where required.
8. Determine mean probability distribution curve (50% probability) and 10% and 90% nonexceedance confidence limit (CL) bands. Compute range of return period water levels and tabulate.

2.3 MCLC simulation of SLC scenarios

In order to incorporate tidal variations and SLC scenarios, the methodology developed for this part of the study consists of a double-loop MCLC simulation. Here it is required for the water levels to be decomposed into primary components (e.g., storm surge, astronomical tide, SLC contribution). Therefore, for this part, only continuous hourly water level records were used since it is not feasible to estimate the surge component solely from monthly maxima data with a reasonable degree of confidence.

The general steps involved in the double-loop MCLC simulation (inner loop and outer loop) are as follows:

2.3.1 MCLC simulation–Inner loop

1. Detrend the verified hourly data series using a linear regression with zero-crossing at year 1992.5, which is the mid point of the NTDE of 1983–2001.
2. Adjust the detrended series to present-day conditions by adding the difference between 1983–2001 MSL and present-day MSL.
3. Use hourly records to estimate storm surge (residuals) as the difference between detrended, verified, and predicted water levels. Product is a continuous time series of hourly residual values.
4. Use POT method to sample λ storms per year. Product is partial duration series of storm surge peaks.
5. Compute empirical distribution and fit parametric distribution.
6. Determine tidal amplitude/variability at each location and compute empirical cumulative probability distribution of tidal data for each gage.
7. For each SLC scenario, use MCLC simulation to generate synthetic storm tide responses from superposition of storm surge, astronomical tide, and SLC components.

2.3.2 MCLC simulation–Outer loop

1. Repeat the inner loop simulation N number of times (e.g., $N \geq 10{,}000$).
2. Determine mean probability distribution curve (50% probability) and 10% and 90% nonexceedance CL bands. Compute range of return period water levels and tabulate.

2.4 Sea level change transformation coefficients and future extreme water levels

The transformation coefficients capture the changes in water levels and uncertainties associated with each SLC scenario. They are used to scale the historical extreme water level distributions in order to estimate possible future extreme water levels. The steps involved in the computation of the transformation coefficients are as follows:

1. Compute transformation coefficients from the MCLC simulation results. These coefficients are computed based on the ratio of water levels from any given SLC scenario (e.g., Modified NRC-III) to the water levels from the SLC Base case (stationary scenario).

2. Use the transformation coefficients to scale the historical extreme water levels computed in the initial statistical analysis.
3. Compute scaled range of return period water levels and tabulate for all scenarios.

3 Statistical Analysis of Extreme Water Levels

The minimum acceptable hourly data record lengths (RL) for this extremal analysis was set at 30 yr. Most modern NOAA water level gages have record lengths that are too short for accurate extremal analysis, being placed into service after 1980. Some gages have large data gaps, some lasting decades. Some gages have data reliability issues for the older data, so those data were deleted from the records. The criterion for rejecting data based on reliability was bias or scatter of a data segment different from the overall detrended record. In all cases with data integrity problems, problematic data were limited to that collected prior to 1950, and the problems were obvious with large deviations in bias and/or scatter from the overall record. So acceptance/rejection metrics were not required. Time histories of the most extreme events were reviewed for accuracy to assure that the low-frequency portion of extremal distributions were accurate. In addition, NOAA summaries of the most extreme water level events for each gage were reviewed and compared to the censored samples computed for this study. In some cases, gages were moved a small distance, and two gages were combined to achieve a longer record length. For this study, Kings Point, NY, was combined with Willets, NY (8516990), to achieve sufficient record length.

Hourly water levels were obtained from NOAA's tides and currents web site (http://tidesandcurrents.noaa.gov) in meters above MSL. Monthly maxima and top-10 water level data, by gage, provided by NOAA (Zervas 2012) are in meters above mean higher high water (MHHW). Typically, record lengths of monthly maxima are longer than those of hourly data. Therefore, the main limiting factor in this analysis is the availability of hourly data. Consequently, only 23 gages were finally selected from Virginia to Maine having continuous or nearly continuous hourly RL that exceed 30 yr. Of these 23 gages, 17 have hourly RL of at least 50 yr, 10 gages have hourly RL of at least 75 yr, and 4 gages have hourly RL exceeding 100 yr.

The 23 gages investigated within this study are listed in Table 2 along with start and end dates for hourly data. Table 3 lists monthly maxima data.

Table 2. List of 23 water level gages used for extremal analysis with hourly data record lengths.

Station ID	Station Name	Start Date	End Date	Record Length (yr)
8410140	Eastport, ME	10/1/1958	3/31/2013	55
8413320	Bar Harbor, ME	3/2/1950	3/31/2013	63
8418150	Portland, ME	3/4/1910	3/31/2013	103
8443970	Boston, MA	5/3/1921	4/30/2013	92
8447930	Woods Hole, MA	2/25/1958	4/30/2013	55
8449130	Nantucket Island, MA	2/1/1965	4/30/2013	48
8452660	Newport, RI	9/10/1930	3/31/2013	83
8454000	Providence, RI	5/24/1979	3/31/2013	34
8461490	New London, CT	6/12/1938	4/30/2013	75
8510560	Montauk Point Light, NY	1/7/1959	4/30/2013	54
8516945	Kings Point, NY	1/1/1957	4/30/2013	56
8518750	The Battery, NY	6/1/1920	4/30/2013	93
8531680	Sandy Hook, NJ	1/7/1910	4/30/2013	103
8534720	Atlantic City, NJ	8/19/1911	4/30/2013	102
8536110	Cape May, NJ	11/21/1965	4/30/2013	48
8557380	Lewes, DE	1/1/1957	4/30/2013	56
8571892	Cambridge, MD	5/31/1979	3/31/2013	34
8574680	Baltimore, MD	7/1/1902	3/31/2013	111
8575512	Annapolis, MD	8/6/1928	4/30/2013	85
8577330	Solomons Island, MD	4/1/1979	3/31/2013	34
8594900	Washington, DC	4/15/1931	3/31/2013	82
8638610	Sewells Point, VA	7/22/1927	3/31/2013	86
8638863	Chesapeake Bay Bridge Tunnel, VA	1/29/1975	4/30/2013	38

Table 3. List of 23 water level gages used for extremal analysis with monthly maxima record lengths.

Station ID	Station Name	First Year	Last Year	Record Length (yr)
8410140	Eastport, ME	1947	2012	66
8413320	Bar Harbor, ME	1912	2012	101
8418150	Portland, ME	1921	2012	92
8443970	Boston, MA	1932	2012	81
8447930	Woods Hole, MA	1965	2012	48
8449130	Nantucket Island, MA	1930	2012	83
8452660	Newport, RI	1938	2012	75
8454000	Providence, RI	1938	2012	75
8461490	New London, CT	1947	2012	66
8510560	Montauk Point Light, NY	1931	2012	82
8516945	Kings Point, NY	1893	2012	120
8518750	The Battery, NY	1932	2012	81
8531680	Sandy Hook, NJ	1911	2012	102
8534720	Atlantic City, NJ	1965	2012	48
8536110	Cape May, NJ	1919	2012	94
8557380	Lewes, DE	1943	2012	70
8571892	Cambridge, MD	1902	2012	111
8574680	Baltimore, MD	1928	2012	85
8575512	Annapolis, MD	1937	2012	76
8577330	Solomons Island, MD	1931	2012	82
8594900	Washington, DC	1927	2012	86
8638610	Sewells Point, VA	1975	2012	38
8638863	Chesapeake Bay Bridge Tunnel, VA	1947	2012	66

Table 4 shows MHHW-to-MSL datum conversions. All analyses performed as part of this study were done using SI units and MSL local datum. Results were later converted from MSL to NAVD88 at the request of the sponsor. MSL-to-NAVD88 datum conversions are provided in Table 5. Plots of hourly and monthly maximum water levels are provided in Appendix A for all 23 gages.

Table 4. MHHW-to-MSL datum conversions for 23 water level gages.

Station ID	Station Name	Elevations on Station Datum MHHW (m)	Elevations on Station Datum MSL (m)	MHHW to MSL (m)
8410140	Eastport, ME	7.336	4.420	2.916
8413320	Bar Harbor, ME	4.524	2.786	1.738
8418150	Portland, ME	5.626	4.113	1.513
8443970	Boston, MA	4.205	2.660	1.545
8447930	Woods Hole, MA	1.469	1.096	0.373
8449130	Nantucket Island, MA	2.004	1.454	0.550
8452660	Newport, RI	1.751	1.106	0.645
8454000	Providence, RI	2.539	1.749	0.790
8461490	New London, CT	2.003	1.542	0.461
8510560	Montauk Point Light, NY	1.947	1.554	0.393
8516945	Kings Point, NY	6.306	5.113	1.193
8518750	The Battery, NY	2.543	1.785	0.758
8531680	Sandy Hook, NJ	2.359	1.551	0.808
8534720	Atlantic City, NJ	2.914	2.186	0.728
8536110	Cape May, NJ	2.398	1.521	0.877
8557380	Lewes, DE	2.266	1.528	0.738
8571892	Cambridge, MD	1.372	1.060	0.312
8574680	Baltimore, MD	1.757	1.495	0.262
8575512	Annapolis, MD	1.815	1.596	0.219
8577330	Solomons Island, MD	1.584	1.366	0.218
8594900	Washington, DC	2.353	1.859	0.494
8638610	Sewells Point, VA	2.176	1.748	0.428
8638863	Chesapeake Bay Bridge Tunnel, VA	8.588	8.135	0.453

Table 5. MSL-to-NAVD88 datum conversions for 23 water level gages.

Station ID	Station Name	Elevations on Station Datum MSL (m)	Elevations on Station Datum NAVD88 (m)	MSL to NAVD88 (m)
8410140	Eastport, ME	4.420	4.491	−0.071
8413320*	Bar Harbor, ME	2.786	2.879	−0.093
8418150	Portland, ME	4.113	4.208	−0.095
8443970	Boston, MA	2.660	2.752	−0.092
8447930	Woods Hole, MA	1.096	1.212	−0.116
8449130*	Nantucket Island, MA	1.454	1.552	−0.098
8452660	Newport, RI	1.106	1.199	−0.093
8454000	Providence, RI	1.749	1.818	−0.069
8461490	New London, CT	1.542	1.634	−0.092
8510560	Montauk Point Light, NY	1.554	1.655	−0.101
8516945*	Kings Point, NY	5.113	5.181	−0.068
8518750	The Battery, NY	1.785	1.848	−0.063
8531680	Sandy Hook, NJ	1.551	1.624	−0.073
8534720	Atlantic City, NJ	2.186	2.308	−0.122
8536110	Cape May, NJ	1.521	1.658	−0.137
8557380	Lewes, DE	1.528	1.649	−0.121
8571892	Cambridge, MD	1.060	1.087	−0.027
8574680	Baltimore, MD	1.495	1.505	−0.010
8575512	Annapolis, MD	1.596	1.612	−0.016
8577330	Solomons Island, MD	1.366	1.394	−0.028
8594900	Washington, DC	1.859	1.812	−0.047
8638610	Sewells Point, VA	1.748	1.827	−0.079
8638863*	Chesapeake Bay Bridge Tunnel, VA	8.135	8.214	−0.079

*Four stations do not currently have published NAVD88 values because they do not meet NOAA CO-OPS QC requirements to receive this relationship. The unpublished conversions shown here for these four stations are NOAA's best estimates during the study period (Michalski 2013).

3.1 Extremal analysis of historical water levels

For the statistical analysis of extreme events, two main types of samples can be produced: block maximum series (BMS) or partial duration series (PDS). The process of constructing a BMS usually consists of recording or

sampling the maximum event for each year over the duration of the data producing an annual maximum series (AMS). Block maximum series can also consist of biannual, monthly, and even daily maxima, as alternatives to AMS. The most common PDS is obtained by selecting all peaks over a certain threshold, POT. In this method, only independent, identically distributed peaks are selected to avoid counting multiple peaks from a single storm as unique events.

According to extreme value theory (Coles 2001), data from BMS have a corresponding distribution in the generalized extreme value (GEV) distribution. Conversely, when data are sampled by means of POT, the resulting PDS should conform to the GPD. Both methods are commonly used, but the PDS/GPD has begun to dominate in recent years because the method considers all extremes while the BMS method could potentially discard a significant amount of extreme events. The PDS/GPD should be the method of choice when the availability of data is limited, instead of BMS/GEV. The PDS/GPD approach is usually preferable over the BMS/GEV approach since the estimates of the latter have greater variability and often result in overpredictions.

The typical criticism of the POT method is that the censoring threshold is arbitrary. However, adoption of recently developed methods makes it deliberate and repeatable. Melby et al. (2012) showed that PDS/GPD fits of extremes are considerably more accurate than those derived using the annual maximum series (AMS)/GEV distribution approach. Therefore, in this study, PDS of extreme water levels were developed for each gage from the POT sampling method. Additional details are given in the following sections.

3.1.1 PDS vs. BMS

The AMS is perhaps the most well known BMS and requires extracting the highest annual value from the data series. This is a simple and straightforward method that can be applied with few restrictions. The most frequent objection to AMS is that secondary extreme events in one year are discarded even if they exceed the annual maximum of other years (Madsen et al. 1997).

The PDS approach can be used to overcome some of the limitations of the BMS. The PDS requires extracting from a given time series all the values above a certain base or threshold. This increases the sample size of extreme

storms over BMS and allows having control over the number of storms extracted per year. Although the PDS approach is more flexible than the BMS, this flexibility is often associated with additional complexity and subjectivity. The extreme values that compose a PDS must meet the conditions of a Poisson-distributed process: independence, homogeneity, and stationarity (Lang et al. 1999). Generally, based on mathematical considerations, the selected threshold value should be high enough in order to satisfy the Poisson process hypothesis.

There is also the option to combine both series, BMS and PDS, so that the annual maximums are complemented by a specified number of independent extreme values above a threshold (Haan 2002). This study focuses on the application of POT analysis to generate PDS of hourly records, while also incorporating monthly maximum series (MMS) in order to (1) maximize the use of available data, (2) expand data record lengths, and (3) fill in data gaps in the PDS.

3.1.2 Detrending of water level time series

The detrending of water level time series is necessary due to the nonstationarity of both monthly maxima and hourly records. The recommended methodology (Zervas 2013) consists in using a linear regression with zero-crossing at year 1992.5, which is the midpoint of the NTDE of 1983–2001. Then, the detrended series needs to be adjusted to present-day conditions by adding the difference between 1983–2001 MSL and present-day MSL. The differences between the 1983–2001 and 2014 datums for all 23 gages indicate upward trends. These are provided in Table 6.

3.1.3 POT approach

The POT approach was used to sample extreme events from the detrended water level time series. For this study, the data from the POT analyses were fit with the GPD which is appropriate for peaks of excesses over a threshold (Pickands 1975; Davison and Smith 1990). As discussed previously, the POT samples must be *independent* and *identically distributed* (IID), and their occurrences should be described by a Poisson process (Luceño et al. 2006). When applying the POT technique, the most significant parameters are (1) the time lag required for the extreme events to be considered as IID, often referred to as interevent time (τ), and (2) the number of individual storms per year which is usually referred to as mean rate or sample intensity (λ).

Table 6. Difference in MSL datum between 1983–2001 and 2014.

Station Number	Station Name	MSL datum Difference (m)
8410140	Eastport, ME	0.05
8413320	Bar Harbor, ME	0.04
8418150	Portland, ME	0.04
8443970	Boston, MA	0.06
8447930	Woods Hole, MA	0.06
8449130	Nantucket Island, MA	0.07
8452660	Newport, RI	0.06
8454000	Providence, RI	0.04
8461490	New London, CT	0.05
8510560	Montauk, NY	0.06
8514560	Port Jefferson, NY	0.05
8516945	Kings Point, NY	0.06
8518750	The Battery, NY	0.08
8531680	Sandy Hook, NJ	0.09
8534720	Atlantic City, NJ	0.09
8536110	Cape May, NJ	0.07
8557380	Lewes, DE	0.08
8571892	Cambridge, MD	0.08
8573927	Chesapeake City, MD	0.08
8574680	Baltimore, MD	0.08
8575512	Annapolis, MD	0.07
8594900	Washington, DC	0.10
8638610	Sewells Point, VA	0.14
8638863	Chesapeake Bay Bridge Tunnel, VA	0.05

3.1.3.1 Independence criteria

The literature provides examples of values of the interevent time (τ) used in several different studies. Méndez et al. (2006) reviewed different studies where the POT approach had been used and provided recommended τ values. For their study of wave heights measured at National Data Buoy Center (NDBC) buoy 46005, τ values between 3 and 10 days were tested. It was found that the Poisson assumption was better satisfied at τ = 6 days. But, since the differences between 3 and 6 days were considered negligible,

τ = 3 days was selected to avoid the possible loss of useful extremal data. Méndez et al. (2006) concluded that, in general, smaller values of τ yield a higher number of extreme events and smaller confidence intervals. Additional studies by Méndez et al. (2007) assumed τ = 3 days to comply with the independence criteria.

Examples of other studies include Van Gelder et al. (2001), which considered wave height time series from several different locations within the North Sea region. In this study, extreme events were extracted from a 15 yr data set (1979–1993). The IID criterion was met using a filter of τ = 2 days. In the United Kingdom, at locations where only sea conditions at high water are of interest, the minimum interevent time is determined based on the tides. Typically, the minimum τ is set to 0.5 days, resulting in two independent events extracted each day, one for each high tide (Hawkes et al. 2002). Hawkes and Svensson (2005) recommend that independent events should not occur on consecutive days and, thus, must be separated by at least three days ($\tau \geq$ 3 days). Luceño et al. (2006) also recommended the use of interevent time (e.g., τ = 3 days). When evaluating a cluster of events, those individual events separated by less than τ should be considered as a single event whose magnitude is that of the most extreme peak in the cluster.

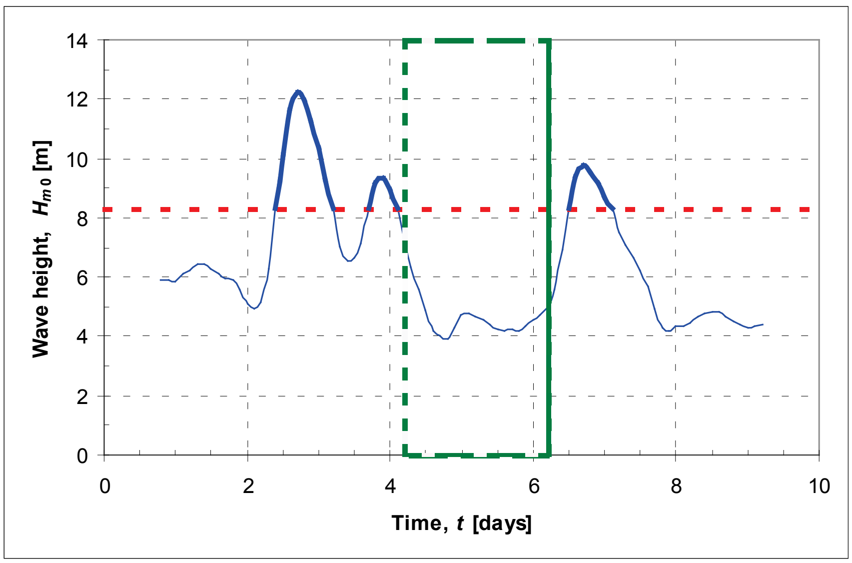
3.1.3.2 Identification of IID events

The preliminary POT series must be evaluated based on a predefined interevent time. There are at least two ways in which this can be done: considering τ to be (1) the time between storm peaks or (2) the time from the end of one storm until the start of the next storm. The problem with the first definition is that it completely disregards the duration of the storms. Therefore, the interevent time should be considered as that time from the end of one storm until the start of the next storm. The storm duration (*D*) can be defined as the total time span in which the parameter of interest equals or exceeds a specific threshold within an IID storm. In the case of multipeak storms, the total storm duration is the summation of the duration of each individual peak. This definition excludes the time between dependent peaks, which would otherwise incorrectly increase the storm duration.

An interevent time of τ = 48 hr, for example, can be thought of as a moving 48 hr window. This time window is used to evaluate the sampled extreme values at each time step. If the time between two extreme values is equal to

or less than 48 hours, both values should be considered part of the same storm. Conversely, if the time between the two values is more than 2 days, they are part of two independent storms. An example of how the interevent time is applied to identify IID storms is shown in Figure 4. This plot represents a period of 10 days in which three peaks are observed. The peaks are located at t = 2.71 days (65 hours (hr)), 3.92 days (94 hr), and 6.71 days (161 hr). The interevent time between the first two peaks is 12 hr. Therefore, these peaks are considered to be dependant peaks of a single storm. On the contrary, the interevent time between the second and third peaks is 58 hr, so the third peak is considered to be a separate, unique storm.

Figure 4. Example of independent storms extracted by POT analysis (threshold = dashed red line).



For this study, the POT approach was used with a τ = 48 hr and sample intensity (λ) of 1.5 or 2.0 events per year. The optimal λ was determined using the quantile-quantile optimization (QQO) technique discussed in Nadal-Caraballo et al. (2012). The interevent time of 48 hr was required to reject duplicate storms and assure that all remaining storms are IID and was determined through an autocorrelation analysis of extratropical storms (Melby et al. 2012).

3.1.4 GPD parameters

The cumulative distribution function (CDF) of the GPD is defined by

$$F(x) = 1 - \left[1 + \frac{\xi(x-\mu)}{\sigma}\right]^{-\frac{1}{\xi}} \qquad \text{for } \xi \neq 0, \text{ and} \qquad (2)$$

$$F(x) = 1 - exp\left(-\frac{x-\mu}{\mu}\right) \qquad \text{for}\xi = 0$$

where:

μ = location parameter (threshold)
ξ = shape parameter
σ = scale parameter

There are several methods for estimating the best values of the GPD parameters, including the least square method (LSM), the method of moments (MoM), and the MLM. The primary method used in this study is MLM. The goal of this method is to determine the distribution parameters that maximize the likelihood of the given sample. In other words, the resulting best-fit parameters correspond to the distribution most likely to have produced the fitted data.

3.2 MCLC simulation of SLC scenarios

MCLC simulation methodology was developed using a double-loop approach. The water level is computed by linear superposition of three components: (1) storm surge, (2) astronomical tide, and (3) local SLC.

For each gage, the inner loop simulates a 100 yr lifecycle by means of bootstrap resampling (Efron 1982; Good 2001; Manly 2006; Chernick 2007). First, storm surge values are randomly sampled from the surge GPD at a rate of two storms per year. Second, the tidal component is randomly sampled from the astronomical tide empirical cumulative distribution function (ECDF). Third, the RSLC is computed for the corresponding year from 100 yr lifecycle starting in 2015 and ending in 2114. The outer loop is executed by performing a total of 10,000 simulations of the 100 yr lifecycle.

For the low-frequency events, storm surge values were simulated by random sampling from the storm surge GPD, using a frequency of two extreme events per year. Tides were simulated by sampling from the entire tide ECDF. Storm surge and astronomical tide were linearly superimposed to estimate the water level response.

For the high-frequency events, storm surge was simulated by random sampling from the ECDF of surge values below the POT threshold. Tides

were simulated by sampling from the extreme tail of the tide ECDF. For this purpose, the standard deviation of tides was computed, and the tidal contribution was sampled from all values equal to or greater than (approximately) two times the standard deviation. An additional high-frequency λ was computed based on the annual occurrence of the extreme tides.

Both low-frequency and high-frequency events were combined and ranked, and the top 200 events were retained (λ * 100 yr of simulation) and used to fit a GPD to the simulated water level extremes. This process was repeated 10,000 times. Select return periods (from 1 to 1000 yr) were computed from each of the 10,000 GPD fits. The mean and standard deviation of water level were computed at each return period, along with 10% and 90% confidence limit bands.

3.2.1 Estimation of storm surge (residuals)

The storm surge, or storm residual, was computed as the difference between detrended observed water levels and predicted water levels. The predicted water levels are based on predicted tides. The observed water level time series are detrended prior to the computation of storm surge because the observed water levels exhibit the effects of sea level change and long-term changes in local ground elevation due to subsidence or postglacial rebound, while the predicted water levels acquired from NOAA are stationary.

Residuals are termed *surge* in this report, but it should be recognized that residual may include phenomena other than storm surge. For example, if the gage is close to a river outflow, the water levels can be influenced by riverine flow. Figure 5 and Figure 6 are examples of storm surge return period plots for Kings Point, NY, and Sandy Hook, NJ, respectively. Storm surge plots for all 23 gages are given in Appendix C.

3.2.2 Astronomical tide range by station

The statistical analysis of astronomical tide was based on ECDF of the NOAA NOS-predicted water level data. Examples of these ECDF plots for Kings Point, NY (Figure 7), and Sandy Hook, NY (Figure 8), are given below. ECDF plots for all 23 gages are provided in Appendix C. Table 7 lists the tide range for each station.

Figure 5. Example of storm surge extremal analysis results for the Kings Point, NY, water level gage with storm surge plotted as a function of return period. Open circles represent empirical distribution values while red-filled circles represent empirical values plotted onto the blue solid curve, which is the GPD fit.

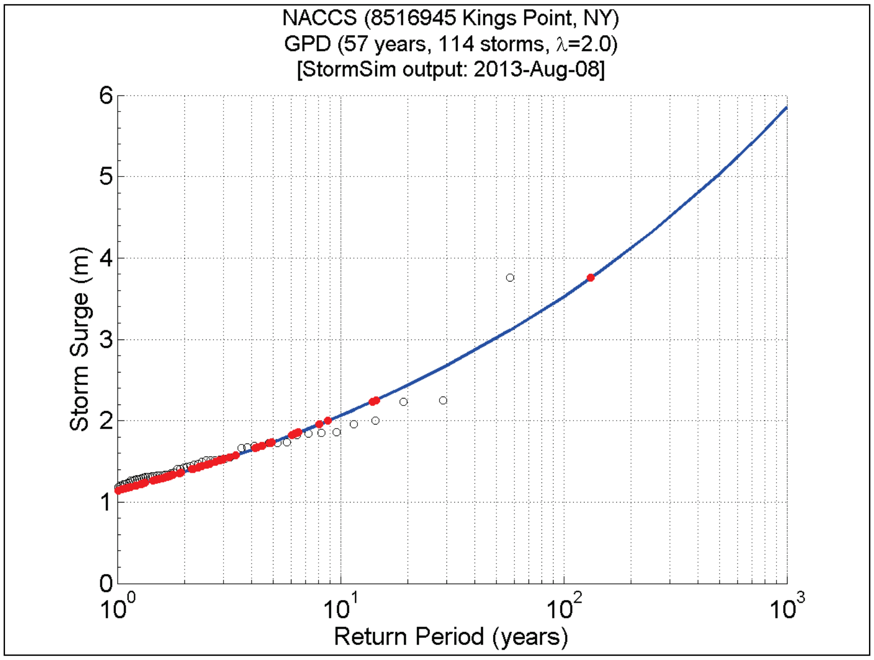


Figure 6. Example of storm surge extremal analysis results for the Sandy Hook, NJ, water level gage with storm surge plotted as a function of return period. Open circles represent empirical distribution values while red-filled circles represent empirical values plotted onto the blue curve line, which is the GPD fit.

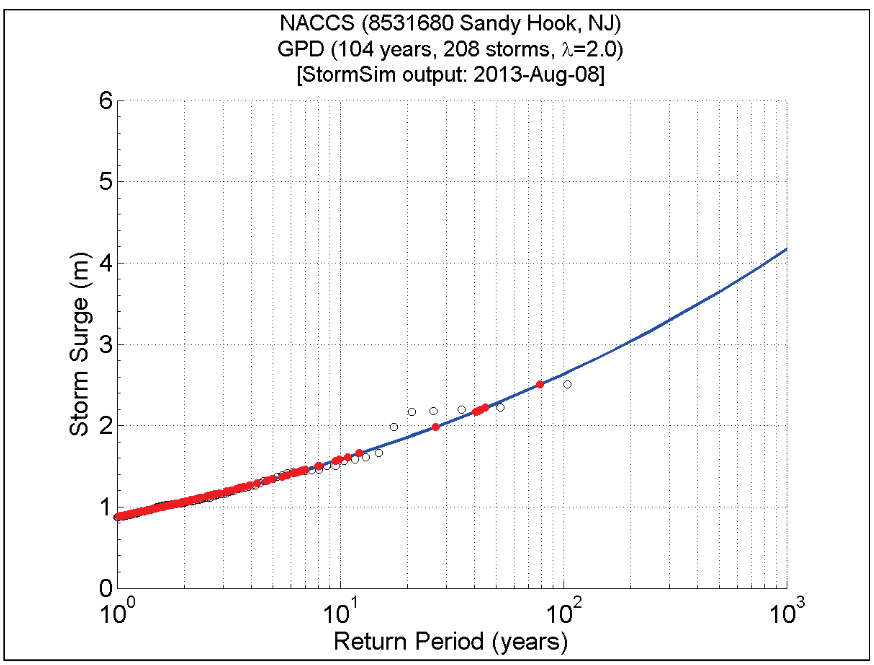


Figure 7. Astronomical tide empirical distribution function for Kings Point, NY.

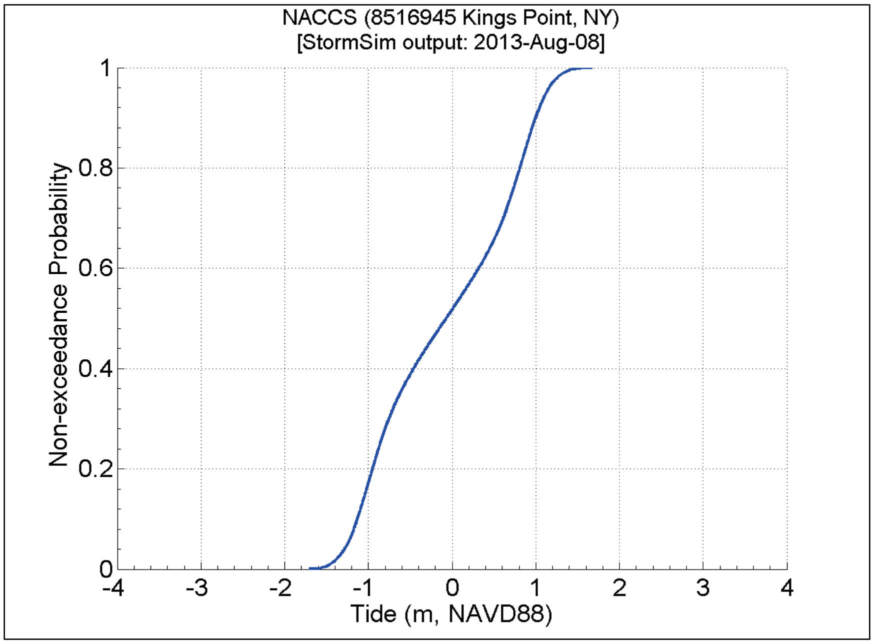


Figure 8. Astronomical tide empirical distribution function for Sandy Hook, NY.

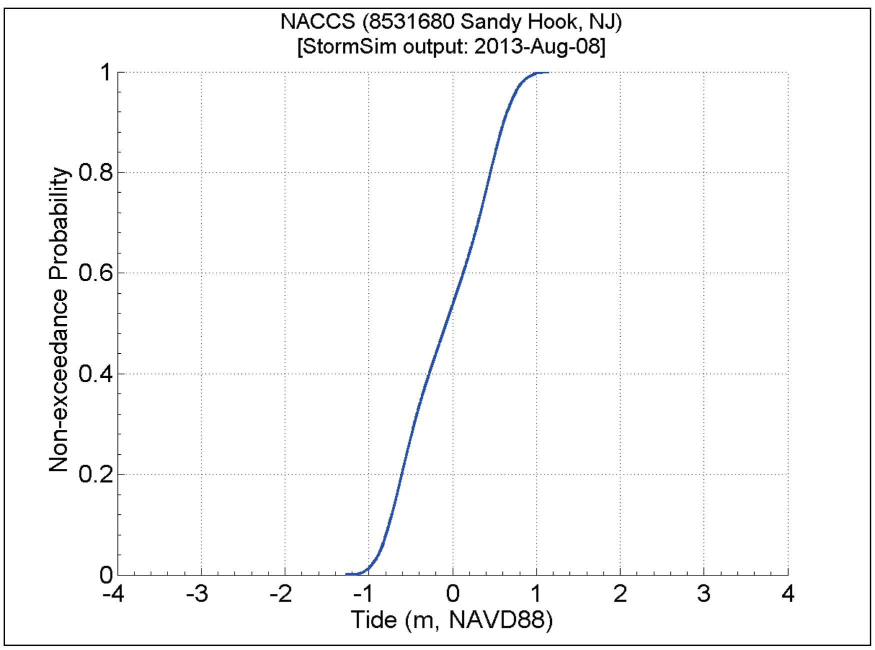


Table 7. Summary of tidal ranges in meters for the 23 NOAA gages with datums relative to station datum.

Station Number	Station Name	MHHW	MSL	MLLW	Range MHHW-MLLW
8410140	Eastport, ME	7.34	4.42	1.46	5.87
8413320	Bar Harbor, ME	4.52	2.79	1.06	3.47
8418150	Portland, ME	5.63	4.11	2.61	3.02
8443970	Boston, MA	4.21	2.66	1.07	3.13
8447930	Woods Hole, MA	1.47	1.11	0.80	0.67
8449130	Nantucket Island, MA	2.00	1.45	0.91	1.09
8452660	Newport, RI	1.75	1.11	0.58	1.17
8454000	Providence, RI	2.54	1.75	1.06	1.48
8461490	New London, CT	2.00	1.54	1.07	0.93
8510560	Montauk, NY	1.95	1.55	1.18	0.77
8514560	Port Jefferson, NY	3.34	2.23	1.16	2.18
8516945	Kings Point, NY	6.31	5.11	3.93	2.38
8518750	The Battery, NY	2.54	1.79	1.00	1.54
8531680	Sandy Hook, NJ	2.36	1.55	0.77	1.59
8534720	Atlantic City, NJ	2.91	2.19	1.51	1.40
8536110	Cape May, NJ	2.40	1.52	0.74	1.66
8557380	Lewes, DE	2.27	1.53	0.85	1.42
8571892	Cambridge, MD	1.37	1.06	0.75	0.62
8573927	Chesapeake City, MD	1.94	1.43	0.96	0.98
8574680	Baltimore, MD	1.76	1.49	1.25	0.51
8575512	Annapolis, MD	1.81	1.60	1.38	0.44
8594900	Washington, DC	2.35	1.86	1.39	0.97
8638610	Sewells Point, VA	2.18	1.75	1.34	0.84
8638863	Chesapeake Bay Bridge Tunnel, VA	8.59	8.14	7.70	0.89

3.2.3 SLC scenarios

The third water level component simulated as part of the MCLC is the SLC. In order to determine the RSLC at any specific location along the coast, the SLC due to local vertical land movement (M) as well as other local SLC contributions must be added to the GSLC resulting from Equation (1). The expression for computing RSLC is as follows:

$$RSLC(t_2) - RSLC(t_1) = (0.0017 + M)(t_2 - t_1) + b(t_2^2 - t_1^2) \quad (3)$$

RSLC computed by NOAA for the 23 gages used in this study are listed in Table 8. Estimates of local vertical land movement used for these stations are listed in Table 9.

Table 8. RSLC as published by NOAA (Zervas 2009).

Station ID	Station Name	First Year	Year Range	Trend for all data to 2006 in mm/yr	
				MSL Trend	95% Confidence Interval
8410140	Eastport, ME	1929	78	2.00	0.21
8413320	Bar Harbor, ME	1947	60	2.04	0.26
8418150	Portland, ME	1912	95	1.82	0.17
8443970	Boston, MA	1921	86	2.63	0.18
8447930	Woods Hole, MA	1932	75	2.61	0.20
8449130	Nantucket Island, MA	1965	42	2.95	0.46
8452660	Newport, RI	1930	77	2.58	0.19
8454000	Providence, RI	1938	69	1.95	0.28
8461490	New London, CT	1938	69	2.25	0.25
8510560	Montauk Point Light, NY	1947	60	2.78	0.32
8516945	Kings Point, NY	1931	76	2.35	0.24
8518750	The Battery, NY	1856	151	2.77	0.09
8531680	Sandy Hook, NJ	1932	75	3.90	0.25
8534720	Atlantic City, NJ	1911	96	3.99	0.18
8536110	Cape May, NJ	1965	42	4.06	0.74
8557380	Lewes, DE	1919	88	3.20	0.28
8571892	Cambridge, MD	1943	64	3.48	0.39
8574680	Baltimore, MD	1902	105	3.08	0.15
8575512	Annapolis, MD	1928	79	3.44	0.23
8577330	Solomons Island, MD	1937	105	3.41	0.29
8594900	Washington, DC	1924	83	3.16	0.35
8638610	Sewells Point, VA	1927	80	4.44	0.27
8638863	Chesapeake Bay Bridge Tunnel, VA	1975	32	6.05	1.14

Table 9. Estimated rates of vertical land movement (Headquarters, U.S. Army Corps of Engineers 2011).

Station ID	Station Name	First Year	Year Range	Est. Vertical Land Movement (M)	95% Confidence Interval	M + 1.7 mm/yr
8410140	Eastport, ME	1929	78	−0.35	0.11	2.05
8413320	Bar Harbor, ME	1947	60	−0.75	0.19	2.45
8418150	Portland, ME	1912	95	−0.16	0.11	1.86
8443970	Boston, MA	1921	86	−0.84	0.08	2.54
8447930	Woods Hole, MA	1932	75	−0.97	0.12	2.67
8449130	Nantucket Island, MA	1965	42	−1.16	0.33	2.86
8452660	Newport, RI	1930	77	−0.88	0.09	2.58
8454000	Providence, RI	1938	69	−0.30	0.14	2.00
8461490	New London, CT	1938	69	−0.67	0.10	2.37
8510560	Montauk Point Light, NY	1947	60	−1.23	0.15	2.93
8516945	Kings Point, NY	1931	76	−0.67	0.07	2.37
8518750	The Battery, NY	1856	151	−1.22	0.06	2.92
8531680	Sandy Hook, NJ	1932	75	−2.27	0.07	3.97
8534720	Atlantic City, NJ	1911	96	−2.17	0.11	3.87
8536110	Cape May, NJ	1965	42	−2.10	0.25	3.80
8557380	Lewes, DE	1919	88	−1.66	0.11	3.36
8571892	Cambridge, MD	1943	64	−1.90	0.08	3.60
8574680	Baltimore, MD	1902	105	−1.33	0.05	3.03
8575512	Annapolis, MD	1928	79	−1.62	0.07	3.32
8577330	Solomons Island, MD	1937	105	−1.83	0.08	3.53
8594900	Washington, DC	1924	83	−1.34	0.17	3.04
8638610	Sewells Point, VA	1927	80	−2.61	0.11	4.31
8638863	Chesapeake Bay Bridge Tunnel, VA	1975	32	−3.34	0.36	5.04

3.3 SLC transformation coefficients and future extreme water levels

The coefficients used to scale the SLC probability distributions from the MCLC simulation (Section 3.2) to the historical extreme water level probability distributions (Section 3.1) are computed from the following transformation function:

$$K_{SLC_{ij}} = \frac{\left(WL_{SLC_{ij}} - WL_{SLC_{0j}}\right) + WL_{hist_j}}{WL_{hist_j}} \tag{4}$$

where:

$K_{SLC_{ij}}$ = transformation coefficient corresponding to SLC scenario i and probability bin j

WL_{hist_j} = historical water level corresponding to probability bin j

$WL_{SLC_{ij}}$ = MCLC simulated water level for SLC scenario i and probability bin j (mean probability curves)

$WL_{SLC_{0j}}$ = MCLC simulated water level for base case SLC scenario and probability bin j (mean probability curves).

The scaled water levels for any SLC scenario are computed as the product of the historical water level and transformation coefficient for a given probability bin:

$$WL_{hist,SLC_{ij}} = WL_{hist_j} \times K_{SLC_{ij}} \tag{5}$$

The transformation coefficients are computed from the mean probability curves (50%), and then the coefficients are used to scale the mean probability curve, as well as the confidence limit curves (10% and 90% nonexceedance).

4 Historical Extreme Water Level Results

The methodology described in Chapters 2 and 3 was followed to compute probabilities of historical extreme water levels for 23 gages located in the U.S. North Atlantic region.

4.1 POT-GPD approach

Table 10 lists the best values of the GPD parameters for each of the 23 gages assessed in this study. The value of the GPD shape parameter (ξ) for this type of study usually ranges from –0.2 to 0.2. As a result of the sensitivity analyses for the gages in this region, for the extreme water levels, the shape parameter was limited to $\xi \leq 0.25$. The idea is to constrain the distribution shape for samples with short RL (RL ≈ 30–40 yr) which otherwise would exhibit large values of ξ, resulting in steep, nonphysical, concave-up distribution shapes and, thus, in over prediction of water levels.

The water level distribution and the 80% confidence interval are plotted in Figure 9 for the Kings Point, NY, gage and in Figure 10 for the Sandy Hook, NJ, gage. An 80% confidence level is bound by 10% and 90% CL. These plots show the mean, or 50% probability curve (solid black), the 10% nonexceedance probability curve (dashed blue), and the 90% non-exceedance probability curve (dashed red). At any given return period, the 90% confidence limit indicates that there is a 90% chance that the expected water level is bound by the upper and lower confidence bands. In other words, the true water level value will not exceed the upper confidence limit 90% of the time or will exceed the upper confidence limit just 10% of the time. Water level return period plots are provided in Appendix B for all 23 gages.

The empirical distributions, shown as green circles in Figures 9 and 10, are based on Weibull's plotting position formula (R/N+1), where R is the rank, and N is the number of samples. The empirical distributions are provided for visualization purposes only and do not constitute a measure of goodness-of-fit. The main shortfalls of the empirical distribution are that (1) by definition, each probability bin of the distribution can be occupied by only one extreme event, and (2) the probability of the most extreme recorded event is dictated by the record length.

Table 10. Parameters from POT analysis and GPD best fits.

Station Name	Events/year, λ	Threshold, μ (m, NAVD88)	Shape Parameter, ξ	Scale Parameter, σ
Eastport, ME	2.0	3.90	0.01	0.09
Bar Harbor, ME	1.5	2.38	0.01	0.10
Portland, ME	1.5	2.16	0.08	0.09
Boston, MA	1.5	2.24	0.06	0.12
Woods Hole, MA	1.5	0.84	0.25	0.14
Nantucket Island, MA	1.5	1.01	0.08	0.11
Newport, RI	1.5	1.17	0.25	0.12
Providence, RI	1.5	1.37	0.25	0.17
New London, CT	2.0	0.94	0.19	0.16
Montauk Point Light, NY	1.5	0.92	0.16	0.15
Kings Point, NY	2.0	1.86	0.21	0.21
The Battery, NY	2.0	1.36	0.19	0.12
Sandy Hook, NJ	2.0	1.45	0.20	0.14
Atlantic City, NJ	1.5	1.31	0.09	0.13
Cape May, NJ	2.0	1.37	−0.12	0.14
Lewes, DE	1.5	1.27	0.06	0.14
Cambridge, MD	2.0	0.78	0.11	0.09
Baltimore, MD	2.0	0.81	0.25	0.10
Annapolis, MD	1.5	0.77	0.23	0.10
Solomons Island, MD	1.5	0.72	0.05	0.09
Washington, DC	1.5	1.11	0.25	0.19
Sewells Point, VA	2.0	1.02	0.12	0.15
Chesapeake Bay Bridge Tunnel, VA	1.5	1.12	0.00	0.16

Considering the water level return periods for Kings Point, NY (Figure 9), for example, the empirical distribution seems to be, visually, in agreement with the mean curve (50% probability). In contrast, for the Sandy Hook, NJ, gage (Figure 10), the highest recorded water level seems to be out of place in relation to the mean curve. The highest water level at Sandy Hook occurred as a consequence of Hurricane Sandy.

Figure 9. Example of water level extremal analysis results for the Kings Point, NY, water level gage with water levels plotted as a function of return period. Green-filled circles represent empirical distribution values.

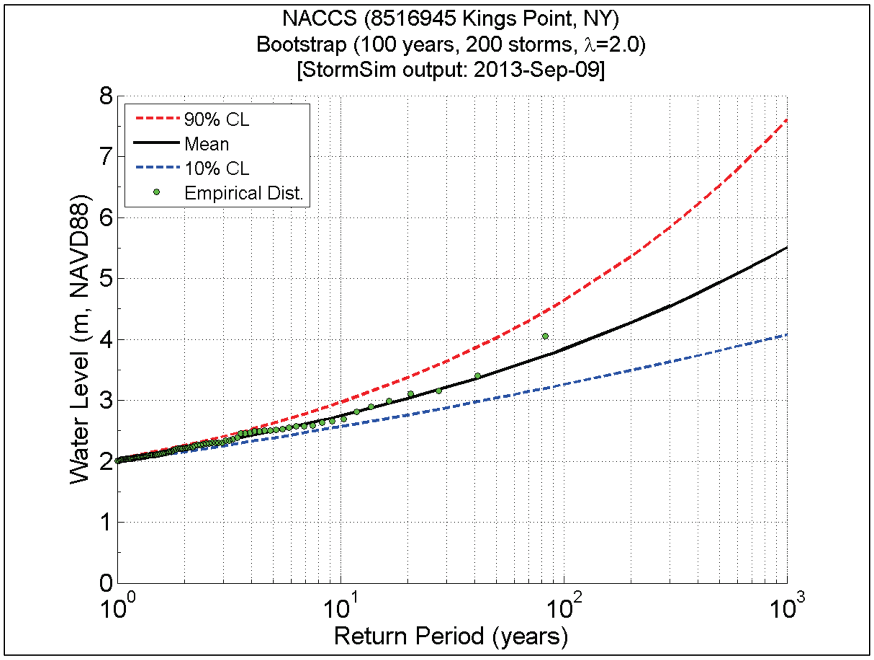
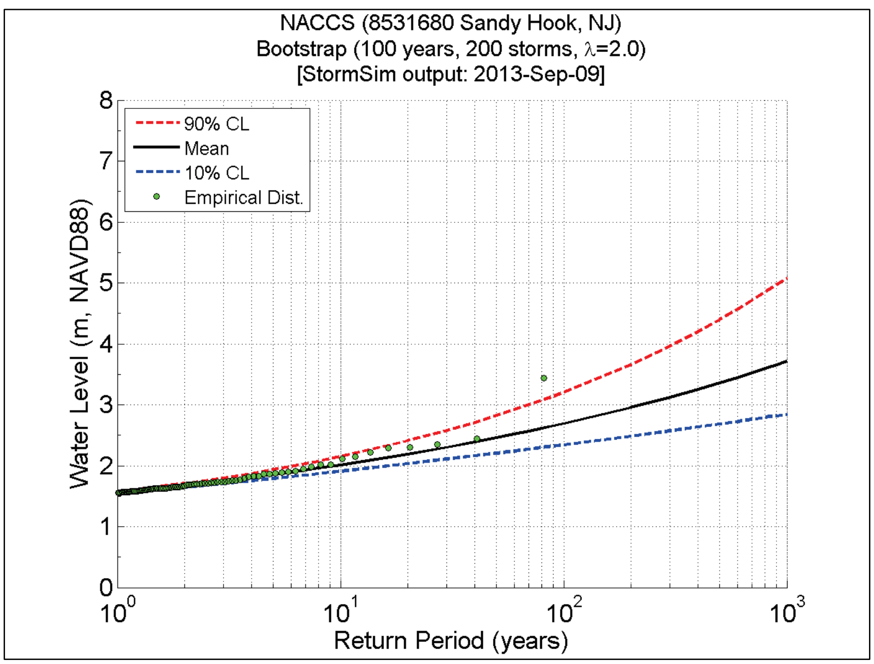


Figure 10. Example of water level extremal analysis results for the Sandy Hook, NJ, water level gage with water levels plotted as a function of return period. Green-filled circles represent empirical distribution values.



The phasing between the astronomical tide and the hurricane storm surge for the Kings Point and Sandy Hook gages are shown in Figure 11 and Figure 12, respectively. At Kings Point, Hurricane Sandy's storm surge peak occurred almost at the same time as the astronomical low tide, resulting in a dampened storm tide response. However, at Sandy Hook the storm surge peak was synchronous with the peak of the high tide, exacerbating the storm tide response. A common misconception suggests that the uncertainty associated with this event is relative to the difference between its magnitude and the distribution value (y-axis) when the true uncertainty is actually due to its unknown frequency position (x-axis). Based solely on the statistical analysis of gage data, a storm surge of this magnitude occurring synchronous with the high tide has an expected (mean) annual exceedance probability on the order of 0.00167 (or 600 yr).

Figure 13 (Kings Point, NY) and Figure 14 (Sandy Hook, NJ) show the measured water level data shifted on the x-axis to match the expected frequency positions estimated from the GPD.

Figure 11. Water level, tide, and surge hydrographs for Kings Point, NY.

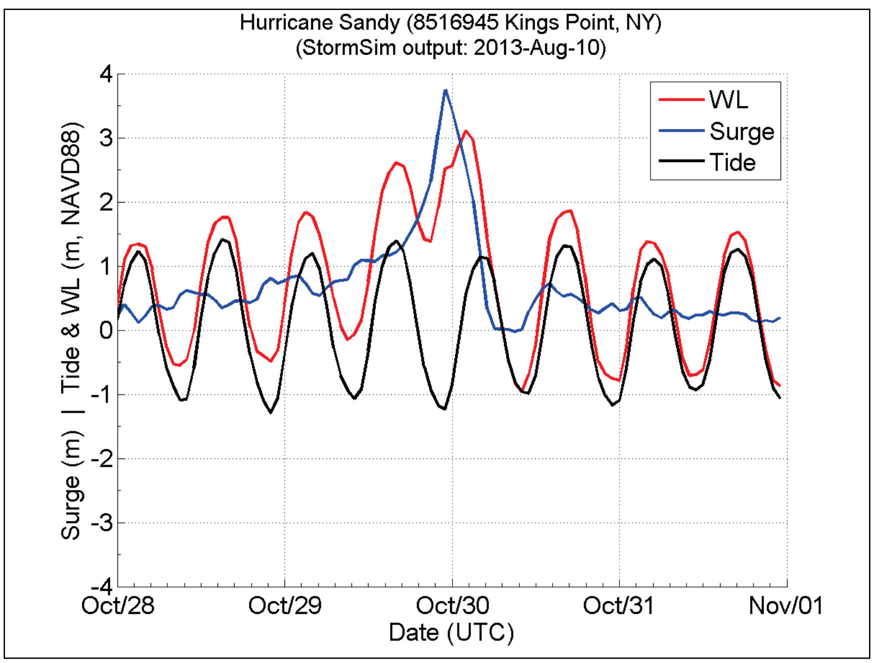


Figure 12. Water level, tide, and surge hydrographs for Sandy Hook, NJ.

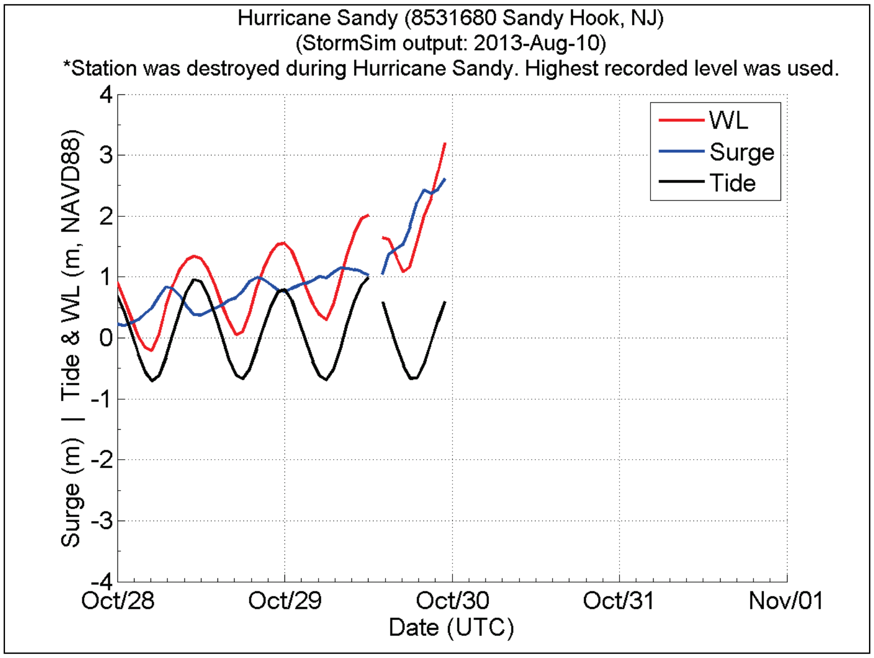


Figure 13. Example of water level extremal analysis results for the Kings Point, NY, water level gage with water levels plotted as a function of return period. Black circles represent empirical distribution values while green-filled circles represent empirical values plotted onto the black solid curve, which is the mean GPD fit.

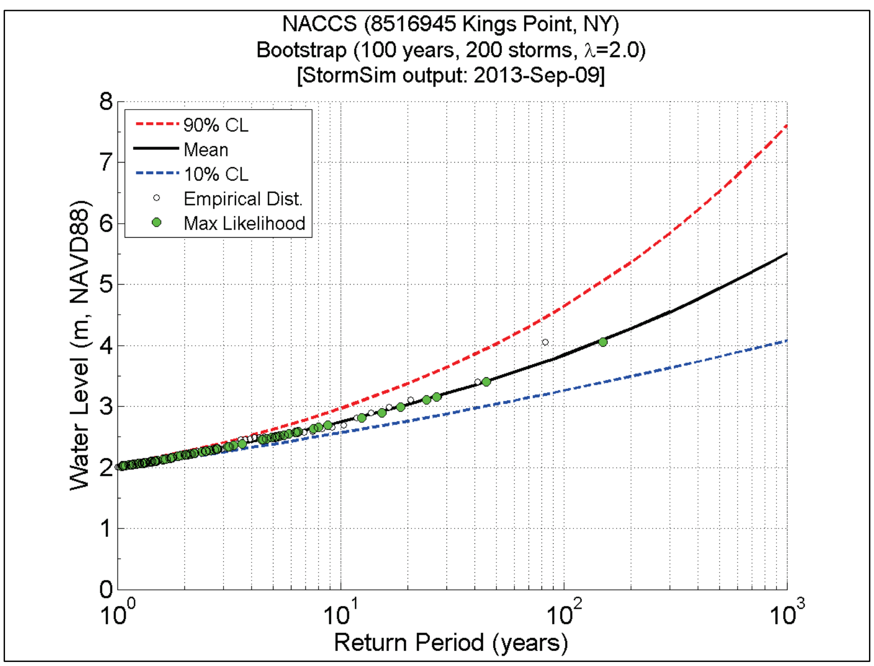
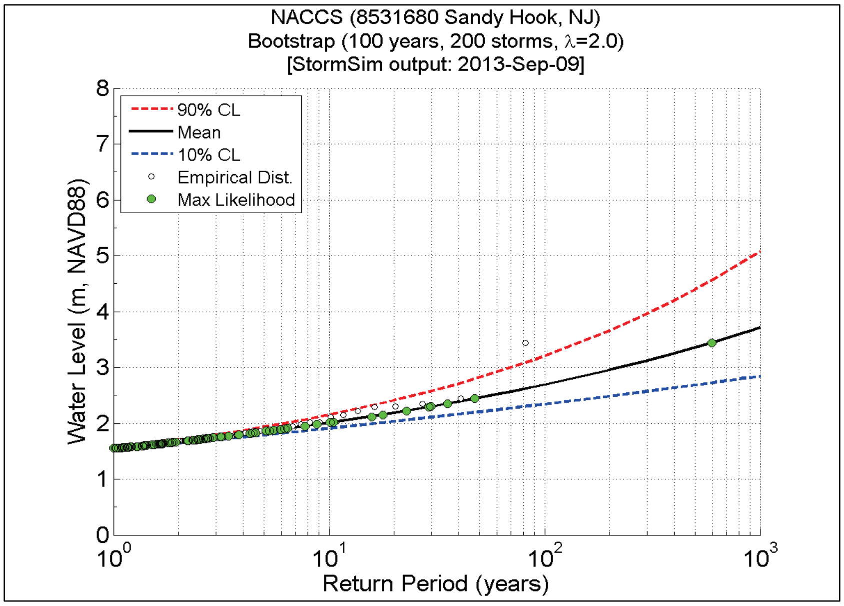


Figure 14. Example of water level extremal analysis results for the Sandy Hook, NJ, water level gage with water levels plotted as a function of return period. Black circles represent empirical distribution values while green-filled circles represent empirical values plotted onto the black solid curve, which is the mean GPD fit.



4.2 Comparison between POT-GPD and GPD-MCLC simulation results

The water levels resulting from the MCLC simulation of historical extreme water levels (50% probability curve) were compared to the water levels of the original GPD fits and are listed in Table 11. MCLC refers to the simulations where the bootstrapping technique was used to resample from the original POT-GPD fits. The MCLC results (mean curve) are hereafter referred to as GPD-MCLC.

For 10 yr return period, the mean difference in water levels is 0.00 m and root-mean-square difference (RMSD) is 0.02 m. Likewise, for 100 yr return period, the mean difference is –0.04 m, while the RMSD is 0.05 m. The expected values are those resulting from the MCLC simulation 50% probability curves.

4.3 Other studies

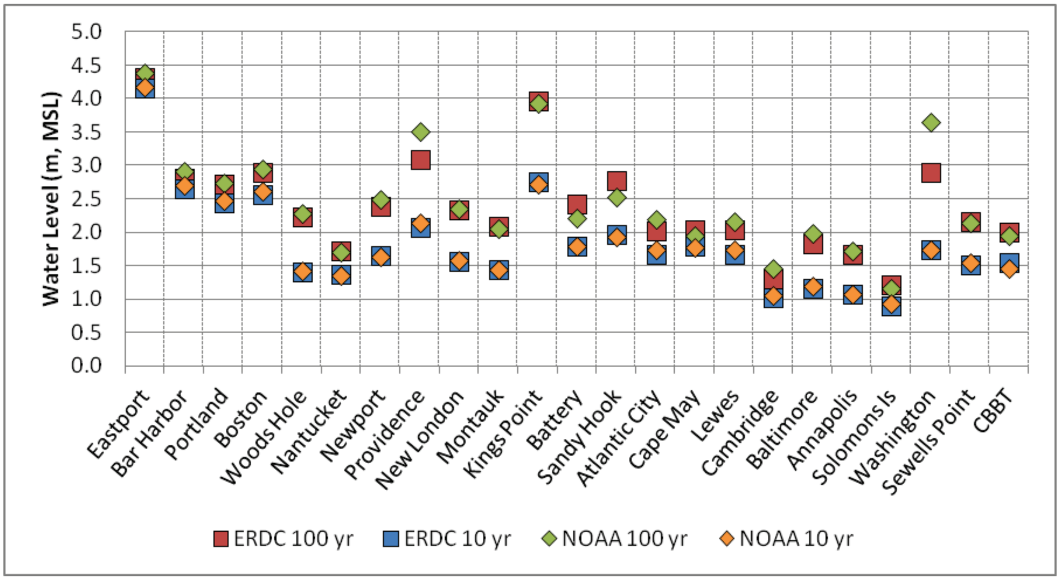
The extreme water level results from this study from the historical water level records were compared to a set of extreme water levels estimated by NOAA (Zervas 2013). The statistical analysis methodology employed by NOAA was based on the use of monthly maximum data fitted by the GEV distribution.

Table 11. Comparison of POT-GPD vs. GPD-MCLC results.

Historical Extreme Water Level (meters, NAVD88)						
	RP = 10 yr			RP = 100 yr		
Station Name	GPD-MCLC	POT-GPD	Diff	GPD-MCLC	POT-GPD	Diff
Eastport, ME	4.15	4.17	−0.02	4.34	4.38	−0.04
Bar Harbor, ME	2.65	2.67	−0.02	2.86	2.91	−0.04
Portland, ME	2.42	2.43	−0.01	2.66	2.70	−0.04
Boston, MA	2.57	2.59	−0.02	2.88	2.94	−0.06
Woods Hole, MA	1.40	1.38	0.02	2.25	2.23	0.02
Nantucket Island, MA	1.31	1.33	−0.02	1.60	1.66	−0.05
Newport, RI	1.66	1.65	0.01	2.39	2.39	0.00
Providence, RI	2.07	2.05	0.02	3.12	3.10	0.02
New London, CT	1.57	1.57	0.00	2.32	2.38	−0.06
Montauk Point Light, NY	1.41	1.42	−0.01	1.99	2.06	−0.06
Kings Point, NY	2.74	2.73	0.01	3.84	3.89	−0.05
The Battery, NY	1.85	1.85	0.00	2.43	2.47	−0.04
Sandy Hook, NJ	2.01	2.00	0.01	2.69	2.73	−0.04
Atlantic City, NJ	1.69	1.71	−0.02	2.07	2.14	−0.07
Cape May, NJ	1.70	1.71	−0.01	1.87	1.90	−0.03
Lewes, DE	1.65	1.67	−0.02	1.99	2.05	−0.06
Cambridge, MD	1.09	1.11	−0.02	1.39	1.45	−0.06
Baltimore, MD	1.30	1.28	0.02	1.96	1.96	0.00
Annapolis, MD	1.18	1.16	0.02	1.76	1.75	0.00
Solomons Island, MD	0.97	0.99	−0.02	1.20	1.24	−0.04
Washington, DC	1.89	1.88	0.01	3.06	3.07	0.00
Sewells Point, VA	1.53	1.55	−0.02	2.03	2.11	−0.08
Chesapeake Bay Bridge Tunnel, VA	1.54	1.56	−0.02	1.88	1.94	−0.06

These comparisons are shown in Figure 15 and listed in Table 12. For 10 yr return period, the differences between the two sets of results are negligible. The mean difference is 0.08 m, and the RMSD is also 0.08 m. For 100 yr return period, the mean difference is 0.00 m and RMSD is 0.17 m.

Figure 15. Comparison between GPD-MCLC and NOAA-GEV water levels.



As shown in Figure 15 and listed in Table 12, for 21 out of 23 gages, the differences are minimal. The two exceptions are the Providence, RI, and Washington, DC, gages, with differences of –0.33 m and –0.64 m, respectively. If these two gages are excluded, for 100 yr return periods, mean difference in water level remains unchanged at 0.00 m, and the RMSD decreases from 0.17 m to 0.09 m. The relative large differences for the two gages were due to the difference between the GEV and GPD fits. The GEV for these gages overshot the empirical distribution. As noted in the discussion of different partial duration sampling techniques, the GPD with POT is a preferred approach partially because it is less likely to exhibit these problems with fitting the empirical data.

4.4 Summary of results

The extreme water levels for return periods of 1, 10, 25, 50, 100, and 500 yr for all 23 gages are listed in Tables 13 and 14.

Table 12. Comparison of GPD-Monte Carlo Life-Cycle simulation results and NOAA-GEV.

Historical Extreme Water Level (meters, NAVD88)						
	RP = 10 yr			RP = 100 yr		
Station Name	GPD-MCLC	NOAA-GEV	Diff	GPD-MCLC	NOAA-GEV	Diff
Eastport, ME	4.15	4.10	0.05	4.34	4.32	0.02
Bar Harbor, ME	2.65	2.61	0.04	2.86	2.82	0.05
Portland, ME	2.42	2.38	0.04	2.66	2.65	0.02
Boston, MA	2.57	2.53	0.04	2.88	2.86	0.02
Woods Hole, MA	1.40	1.30	0.10	2.25	2.17	0.07
Nantucket Island, MA	1.31	1.25	0.06	1.60	1.60	0.00
Newport, RI	1.66	1.55	0.11	2.39	2.40	0.00
Providence, RI	2.07	2.07	0.00	3.12	3.45	-0.33
New London, CT	1.57	1.50	0.07	2.32	2.26	0.06
Montauk Point Light, NY	1.41	1.35	0.06	1.99	1.96	0.03
Kings Point, NY	2.74	2.66	0.08	3.84	3.87	-0.04
The Battery, NY	1.85	1.73	0.12	2.43	2.16	0.28
Sandy Hook, NJ	2.01	1.86	0.15	2.69	2.46	0.23
Atlantic City, NJ	1.69	1.63	0.06	2.07	2.07	0.01
Cape May, NJ	1.70	1.63	0.07	1.87	1.82	0.05
Lewes, DE	1.65	1.62	0.03	1.99	2.04	−0.05
Cambridge, MD	1.09	1.03	0.06	1.39	1.43	−0.04
Baltimore, MD	1.30	1.19	0.11	1.96	1.97	−0.01
Annapolis, MD	1.18	1.06	0.12	1.76	1.71	0.04
Solomons Island, MD	0.97	0.91	0.06	1.20	1.14	0.06
Washington, DC	1.89	1.80	0.09	3.06	3.70	−0.63
Sewells Point, VA	1.53	1.47	0.06	2.03	2.07	−0.04
Chesapeake Bay Bridge Tunnel, VA	1.54	1.39	0.15	1.88	1.88	0.00

Table 13. Water levels for 1, 10, and 25 yr return periods (RP) from historical extremes.

Historical Extreme Events						
	Water Level (m)–Datum: NAVD88					
	1 yr RP		10 yr RP		25 yr RP	
Station Name	Mean	90% CL	Mean	90% CL	Mean	90% CL
Eastport, ME	3.96	3.97	4.15	4.19	4.23	4.28
Bar Harbor, ME	2.43	2.43	2.65	2.69	2.73	2.79
Portland, ME	2.20	2.20	2.42	2.46	2.51	2.58
Boston, MA	2.28	2.29	2.57	2.62	2.69	2.77
Woods Hole, MA	0.89	0.90	1.40	1.54	1.68	1.93
Nantucket Island, MA	1.05	1.06	1.31	1.36	1.42	1.50
Newport, RI	1.21	1.22	1.66	1.79	1.90	2.12
Providence, RI	1.44	1.45	2.07	2.25	2.42	2.73
New London, CT	1.05	1.07	1.57	1.73	1.83	2.11
Montauk Point Light, NY	0.98	0.99	1.41	1.51	1.62	1.80
Kings Point, NY	2.01	2.03	2.74	2.96	3.12	3.50
The Battery, NY	1.45	1.46	1.85	1.97	2.05	2.27
Sandy Hook, NJ	1.55	1.56	2.01	2.15	2.24	2.49
Atlantic City, NJ	1.36	1.37	1.69	1.76	1.84	1.94
Cape May, NJ	1.46	1.47	1.70	1.74	1.77	1.82
Lewes, DE	1.32	1.33	1.65	1.70	1.78	1.87
Cambridge, MD	0.84	0.85	1.09	1.15	1.21	1.31
Baltimore, MD	0.89	0.90	1.30	1.43	1.52	1.74
Annapolis, MD	0.81	0.82	1.18	1.27	1.37	1.54
Solomons Island, MD	0.75	0.76	0.97	1.01	1.06	1.12
Washington, DC	1.18	1.20	1.89	2.10	2.28	2.64
Sewells Point, VA	1.13	1.14	1.53	1.63	1.72	1.89
Chesapeake Bay Bridge Tunnel, VA	1.18	1.19	1.54	1.60	1.67	1.76

Table 14. Water levels for 50, 100, and 500 yr RP from historical extremes.

Historical Extreme Events						
	Water Level (m)–Datum: NAVD88					
	50 yr RP		100 yr RP		500 yr RP	
Station Name	Mean	90% CL	Mean	90% CL	Mean	90% CL
Eastport, ME	4.28	4.36	4.34	4.44	4.47	4.65
Bar Harbor, ME	2.80	2.88	2.86	2.97	3.01	3.21
Portland, ME	2.58	2.68	2.66	2.80	2.85	3.12
Boston, MA	2.78	2.91	2.88	3.05	3.11	3.44
Woods Hole, MA	1.94	2.30	2.25	2.73	3.16	4.08
Nantucket Island, MA	1.51	1.63	1.60	1.77	1.83	2.15
Newport, RI	2.13	2.45	2.39	2.83	3.19	4.00
Providence, RI	2.75	3.20	3.12	3.74	4.26	5.42
New London, CT	2.06	2.48	2.32	2.91	3.03	4.25
Montauk Point Light, NY	1.80	2.08	1.99	2.41	2.52	3.42
Kings Point, NY	3.46	4.03	3.84	4.63	4.93	6.52
The Battery, NY	2.23	2.55	2.43	2.88	3.00	3.91
Sandy Hook, NJ	2.46	2.82	2.69	3.20	3.35	4.40
Atlantic City, NJ	1.95	2.11	2.07	2.30	2.38	2.82
Cape May, NJ	1.82	1.89	1.87	1.95	1.96	2.09
Lewes, DE	1.88	2.02	1.99	2.18	2.25	2.60
Cambridge, MD	1.30	1.45	1.39	1.61	1.64	2.06
Baltimore, MD	1.72	2.03	1.96	2.38	2.68	3.46
Annapolis, MD	1.55	1.81	1.76	2.11	2.37	3.06
Solomons Island, MD	1.13	1.22	1.20	1.32	1.37	1.59
Washington, DC	2.64	3.16	3.06	3.76	4.32	5.65
Sewells Point, VA	1.87	2.12	2.03	2.39	2.45	3.17
Chesapeake Bay Bridge Tunnel, VA	1.78	1.90	1.88	2.04	2.11	2.40

5 Future Extreme Water Level Results

5.1 SLC transformation coefficients

Transformation coefficients for all SLC scenarios as a function of return period were computed from Equations (3) and (4), as discussed in Section 3.3. The SLC transformation coefficients for all 23 gages are listed in Tables 15 through 19.

The transformation coefficients provided in Tables 15–19 are nondimensional. However, they were computed from water levels above MSL and, thus, should not be used to scale extreme distributions of water levels in any other vertical datum.

5.2 Summary of results

The methodology described in Chapters 2 and 3 was followed to compute the probabilities of future extreme water levels at the end of the 100 yr period between 2015 and 2114, incorporating different SLC scenarios. In other words, the results represent the nondetrended extreme water levels for the year 2114. For all cases, the continuous cumulative distribution of water level was computed, and a range of return periods computed. Water levels were computed for return periods from 1 to 500 yr.

Tables 20 through 29 summarize 1, 10, 25, 50, 100, and 500 yr return period water levels for all SLC scenarios. Future extreme water levels as a function of return period were plotted for each of the 23 gages and are shown in Appendix D.

Table 15. Transformation coefficients for SLC Scenario 2, Historical (linear).

Transformation Coefficients, K_{SLC} for SLC Scenario 2 (nondimensional, MSL)						
Stations Name	RP 1 yr	RP 10 yr	RP 25 yr	RP 50 yr	RP 100 yr	RP 500 yr
Eastport, ME	1.0299	1.0292	1.0291	1.0291	1.0291	1.0295
Bar Harbor, ME	1.0574	1.0551	1.0548	1.0540	1.0539	1.0542
Portland, ME	1.0476	1.0433	1.0427	1.0403	1.0391	1.0362
Boston, MA	1.0641	1.0553	1.0541	1.0495	1.0472	1.0418
Woods Hole, MA	1.1628	1.1069	1.1003	1.0779	1.0677	1.0481
Nantucket Island, MA	1.1495	1.1238	1.1205	1.1098	1.1046	1.0939
Newport, RI	1.1179	1.0880	1.0839	1.0696	1.0623	1.0475
Providence, RI	1.0754	1.0521	1.0491	1.0388	1.0338	1.0240
New London, CT	1.1182	1.0808	1.0766	1.0632	1.0564	1.0432
Montauk Point Light, NY	1.1603	1.1166	1.1115	1.0942	1.0862	1.0703
Kings Point, NY	1.0636	1.0455	1.0430	1.0348	1.0311	1.0230
The Battery, NY	1.1116	1.0871	1.0836	1.0716	1.0656	1.0525
Sandy Hook, NJ	1.1486	1.1146	1.1099	1.0937	1.0851	1.0677
Atlantic City, NJ	1.1626	1.1382	1.1351	1.1252	1.1207	1.1122
Cape May, NJ	1.1465	1.1311	1.1298	1.1260	1.1248	1.1242
Lewes, DE	1.1373	1.1145	1.1118	1.1030	1.0990	1.0909
Cambridge, MD	1.2538	1.1989	1.1924	1.1704	1.1596	1.1384
Baltimore, MD	1.2118	1.1400	1.1310	1.1005	1.0861	1.0583
Annapolis, MD	1.2617	1.1726	1.1616	1.1245	1.1069	1.0720
Solomons Island, MD	1.2840	1.2310	1.2254	1.2073	1.1992	1.1861
Washington, DC	1.1495	1.0892	1.0828	1.0616	1.0523	1.0346
Sewells Point, VA	1.2183	1.1621	1.1555	1.1334	1.1225	1.1010
Chesapeake Bay Bridge Tunnel, VA	1.2552	1.2001	1.1943	1.1751	1.1664	1.1501

Table 16. Transformation coefficients for SLC Scenario 3, Modified NRC-I.

Transformation Coefficients, K_{SLC} for SLC Scenario 3 (nondimensional, MSL)						
Stations Name	RP 1 yr	RP 10 yr	RP 25 yr	RP 50 yr	RP 100 yr	RP 500 yr
Eastport, ME	1.0949	1.0953	1.0955	1.0966	1.0975	1.1012
Bar Harbor, ME	1.1502	1.1616	1.1626	1.1650	1.1648	1.1573
Portland, ME	1.1609	1.1492	1.1476	1.1419	1.1390	1.1329
Boston, MA	1.1742	1.1527	1.1496	1.1388	1.1329	1.1193
Woods Hole, MA	1.4447	1.2835	1.2644	1.2005	1.1708	1.1148
Nantucket Island, MA	1.3885	1.3167	1.3075	1.2764	1.2612	1.2293
Newport, RI	1.3277	1.2381	1.2258	1.1831	1.1614	1.1175
Providence, RI	1.2387	1.1582	1.1480	1.1132	1.0963	1.0633
New London, CT	1.3310	1.2204	1.2074	1.1648	1.1442	1.1047
Montauk Point Light, NY	1.4063	1.2916	1.2782	1.2332	1.2119	1.1699
Kings Point, NY	1.1738	1.1168	1.1091	1.0833	1.0704	1.0438
The Battery, NY	1.2725	1.2094	1.2004	1.1692	1.1529	1.1182
Sandy Hook, NJ	1.3126	1.2343	1.2235	1.1855	1.1660	1.1254
Atlantic City, NJ	1.3550	1.2996	1.2926	1.2691	1.2582	1.2371
Cape May, NJ	1.3199	1.2861	1.2831	1.2743	1.2712	1.2683
Lewes, DE	1.3163	1.2631	1.2568	1.2360	1.2264	1.2069
Cambridge, MD	1.5741	1.4418	1.4257	1.3711	1.3444	1.2889
Baltimore, MD	1.5303	1.3374	1.3133	1.2327	1.1941	1.1200
Annapolis, MD	1.6185	1.4008	1.3740	1.2831	1.2402	1.1559
Solomons Island, MD	1.6558	1.5271	1.5130	1.4668	1.4462	1.4079
Washington, DC	1.3471	1.1966	1.1802	1.1274	1.1045	1.0614
Sewells Point, VA	1.4425	1.3196	1.3048	1.2550	1.2308	1.1813
Chesapeake Bay Bridge Tunnel, VA	1.4822	1.3736	1.3619	1.3231	1.3053	1.2699

Table 17. Transformation coefficients for SLC Scenario 4, Modified NRC-II.

Transformation Coefficients, K_{SLC} for SLC Scenario 4 (nondimensional, MSL)						
Stations Name	RP 1 yr	RP 10 yr	RP 25 yr	RP 50 yr	RP 100 yr	RP 500 yr
Eastport, ME	1.2201	1.2239	1.2246	1.2270	1.2283	1.2308
Bar Harbor, ME	1.3082	1.3588	1.3619	1.3663	1.3620	1.3327
Portland, ME	1.3709	1.3647	1.3629	1.3537	1.3466	1.3222
Boston, MA	1.3745	1.3477	1.3440	1.3304	1.3234	1.3081
Woods Hole, MA	1.9794	1.6224	1.5803	1.4395	1.3743	1.2506
Nantucket Island, MA	1.8533	1.6887	1.6676	1.5957	1.5601	1.4846
Newport, RI	1.7354	1.5284	1.5001	1.4016	1.3519	1.2507
Providence, RI	1.5782	1.3788	1.3533	1.2665	1.2251	1.1435
New London, CT	1.7719	1.5010	1.4692	1.3639	1.3141	1.2170
Montauk Point Light, NY	1.8874	1.6315	1.6013	1.5001	1.4525	1.3578
Kings Point, NY	1.3981	1.2612	1.2430	1.1808	1.1500	1.0862
The Battery, NY	1.5981	1.4503	1.4294	1.3563	1.3182	1.2365
Sandy Hook, NJ	1.6271	1.4639	1.4413	1.3617	1.3212	1.2352
Atlantic City, NJ	1.7145	1.5944	1.5790	1.5271	1.5021	1.4515
Cape May, NJ	1.6496	1.5733	1.5660	1.5436	1.5347	1.5210
Lewes, DE	1.6696	1.5498	1.5351	1.4856	1.4619	1.4131
Cambridge, MD	2.1799	1.9016	1.8674	1.7509	1.6935	1.5741
Baltimore, MD	2.1211	1.7219	1.6720	1.5047	1.4251	1.2717
Annapolis, MD	2.2691	1.8340	1.7800	1.5983	1.5119	1.3430
Solomons Island, MD	2.3443	2.0713	2.0406	1.9402	1.8942	1.8067
Washington, DC	1.7543	1.4069	1.3693	1.2479	1.1946	1.0972
Sewells Point, VA	1.8669	1.6211	1.5915	1.4919	1.4431	1.3426
Chesapeake Bay Bridge Tunnel, VA	1.8997	1.6940	1.6716	1.5974	1.5626	1.4933

Table 18. Transformation coefficients for SLC Scenario 5, Modified NRC-III.

Transformation Coefficients, K_{SLC} for SLC Scenario 5 (non-dimensional, MSL)						
Stations Name	RP 1 yr	RP 10 yr	RP 25 yr	RP 50 yr	RP 100 yr	RP 500 yr
Eastport, ME	1.3512	1.3610	1.3617	1.3629	1.3617	1.3523
Bar Harbor, ME	1.4714	1.5634	1.5698	1.5836	1.5818	1.5533
Portland, ME	1.5891	1.5940	1.5908	1.5730	1.5568	1.5005
Boston, MA	1.5837	1.5618	1.5562	1.5314	1.5137	1.4573
Woods Hole, MA	2.5511	1.9925	1.9263	1.7059	1.6038	1.4097
Nantucket Island, MA	2.3529	2.0922	2.0590	1.9454	1.8890	1.7693
Newport, RI	2.1734	1.8467	1.8021	1.6464	1.5679	1.4078
Providence, RI	1.9521	1.6281	1.5869	1.4462	1.3789	1.2467
New London, CT	2.2620	1.8235	1.7721	1.6018	1.5211	1.3638
Montauk Point Light, NY	2.4112	2.0028	1.9545	1.7928	1.7168	1.5662
Kings Point, NY	1.6481	1.4337	1.4057	1.3086	1.2605	1.1616
The Battery, NY	1.9618	1.7267	1.6935	1.5775	1.5175	1.3880
Sandy Hook, NJ	1.9693	1.7210	1.6865	1.5649	1.5031	1.3715
Atlantic City, NJ	2.0986	1.9089	1.8848	1.8028	1.7628	1.6811
Cape May, NJ	2.0046	1.8824	1.8706	1.8335	1.8181	1.7930
Lewes, DE	2.0569	1.8637	1.8400	1.7594	1.7205	1.6401
Cambridge, MD	2.8307	2.4010	2.3480	2.1678	2.0791	1.8951
Baltimore, MD	2.7532	2.1458	2.0699	1.8148	1.6932	1.4581
Annapolis, MD	2.9610	2.3055	2.2245	1.9505	1.8204	1.5662
Solomons Island, MD	3.0754	2.6470	2.5988	2.4402	2.3673	2.2255
Washington, DC	2.2164	1.6582	1.5980	1.4029	1.3172	1.1612
Sewells Point, VA	2.3297	1.9580	1.9134	1.7631	1.6900	1.5393
Chesapeake Bay Bridge Tunnel, VA	2.3473	2.0402	2.0070	1.8970	1.8455	1.7431

Table 19. Transformation coefficients for SLC Scenario 6, NOAA Highest.

Transformation Coefficients, K_{SLC} for SLC Scenario 6 (nondimensional, MSL)						
Stations Name	RP 1 yr	RP 10 yr	RP 25 yr	RP 50 yr	RP 100 yr	RP 500 yr
Eastport, ME	1.4838	1.5006	1.5014	1.5012	1.4979	1.4799
Bar Harbor, ME	1.6376	1.7696	1.7797	1.8043	1.8063	1.7831
Portland, ME	1.8093	1.8271	1.8234	1.8005	1.7794	1.7066
Boston, MA	1.7960	1.7795	1.7722	1.7377	1.7112	1.6274
Woods Hole, MA	3.1376	2.3762	2.2863	1.9860	1.8469	1.5817
Nantucket Island, MA	2.8643	2.5077	2.4624	2.3078	2.2314	2.0692
Newport, RI	2.6234	2.1779	2.1171	1.9048	1.7975	1.5788
Providence, RI	2.3390	1.8930	1.8361	1.6421	1.5490	1.3661
New London, CT	2.7696	2.1620	2.0908	1.8548	1.7436	1.5265
Montauk Point Light, NY	2.9510	2.3867	2.3200	2.0975	1.9928	1.7848
Kings Point, NY	1.9044	1.6226	1.5856	1.4582	1.3953	1.2658
The Battery, NY	2.3390	2.0176	1.9724	1.8139	1.7321	1.5558
Sandy Hook, NJ	2.3230	1.9912	1.9451	1.7832	1.7009	1.5263
Atlantic City, NJ	2.4922	2.2317	2.1985	2.0856	2.0307	1.9181
Cape May, NJ	2.3692	2.2004	2.1839	2.1320	2.1102	2.0735
Lewes, DE	2.4570	2.1890	2.1561	2.0443	1.9905	1.8785
Cambridge, MD	3.4999	2.9170	2.8454	2.6020	2.4830	2.2356
Baltimore, MD	3.4026	2.5879	2.4861	2.1434	1.9797	1.6633
Annapolis, MD	3.6701	2.7930	2.6844	2.3178	2.1438	1.8037
Solomons Island, MD	3.8240	3.2362	3.1699	2.9516	2.8512	2.6549
Washington, DC	2.7032	1.9363	1.8535	1.5855	1.4675	1.2529
Sewells Point, VA	2.8080	2.3100	2.2503	2.0500	1.9527	1.7533
Chesapeake Bay Bridge Tunnel, VA	2.8074	2.3981	2.3539	2.2079	2.1396	2.0047

Table 20 Water levels for 1, 10, and 25 yr RP for SLC Scenario 2, Historical (linear).

SLC Scenario 2, Historical (Linear Trend)						
	Water Level (m)–Datum: NAVD88					
	1 yr RP		10 yr RP		25 yr RP	
Station Name	Mean	90% CL	Mean	90% CL	Mean	90% CL
Eastport, ME	4.08	4.09	4.28	4.32	4.35	4.41
Bar Harbor, ME	2.57	2.58	2.80	2.84	2.89	2.95
Portland, ME	2.30	2.31	2.52	2.57	2.62	2.69
Boston, MA	2.44	2.44	2.72	2.77	2.83	2.92
Woods Hole, MA	1.05	1.07	1.57	1.72	1.84	2.12
Nantucket Island, MA	1.23	1.23	1.49	1.54	1.60	1.69
Newport, RI	1.37	1.38	1.82	1.95	2.06	2.30
Providence, RI	1.55	1.56	2.18	2.37	2.53	2.86
New London, CT	1.19	1.20	1.71	1.87	1.97	2.27
Montauk Point Light, NY	1.15	1.16	1.59	1.70	1.80	2.00
Kings Point, NY	2.15	2.17	2.87	3.10	3.24	3.64
The Battery, NY	1.62	1.63	2.02	2.15	2.22	2.45
Sandy Hook, NJ	1.79	1.81	2.25	2.40	2.48	2.75
Atlantic City, NJ	1.60	1.61	1.94	2.02	2.09	2.21
Cape May, NJ	1.69	1.70	1.94	1.98	2.02	2.07
Lewes, DE	1.52	1.53	1.85	1.91	1.98	2.09
Cambridge, MD	1.07	1.08	1.32	1.39	1.43	1.55
Baltimore, MD	1.08	1.09	1.48	1.63	1.70	1.94
Annapolis, MD	1.03	1.04	1.38	1.50	1.57	1.77
Solomons Island, MD	0.98	0.98	1.20	1.25	1.29	1.37
Washington, DC	1.35	1.37	2.06	2.28	2.44	2.82
Sewells Point, VA	1.39	1.41	1.80	1.91	1.98	2.17
Chesapeake Bay Bridge Tunnel, VA	1.51	1.52	1.86	1.93	2.00	2.10

Table 21. Water levels for 50, 100, and 500 yr RP for SLC Scenario 2, Historical (linear).

SLC Scenario 2, Historical (Linear Trend)						
	Water Level (m)–Datum: NAVD88					
	50 yr RP		100 yr RP		500 yr RP	
Station Name	Mean	90% CL	Mean	90% CL	Mean	90% CL
Eastport, ME	4.41	4.49	4.47	4.57	4.60	4.79
Bar Harbor, ME	2.96	3.04	3.02	3.13	3.18	3.38
Portland, ME	2.69	2.79	2.77	2.91	2.96	3.24
Boston, MA	2.93	3.05	3.02	3.20	3.25	3.59
Woods Hole, MA	2.11	2.49	2.41	2.93	3.32	4.28
Nantucket Island, MA	1.69	1.82	1.78	1.96	2.01	2.36
Newport, RI	2.29	2.62	2.55	3.01	3.34	4.20
Providence, RI	2.86	3.32	3.23	3.87	4.36	5.55
New London, CT	2.20	2.64	2.45	3.08	3.16	4.44
Montauk Point Light, NY	1.98	2.29	2.17	2.63	2.70	3.66
Kings Point, NY	3.58	4.17	3.96	4.78	5.04	6.68
The Battery, NY	2.40	2.74	2.60	3.07	3.16	4.12
Sandy Hook, NJ	2.69	3.09	2.92	3.48	3.58	4.70
Atlantic City, NJ	2.21	2.39	2.34	2.59	2.66	3.15
Cape May, NJ	2.07	2.15	2.12	2.21	2.22	2.36
Lewes, DE	2.09	2.24	2.20	2.40	2.46	2.85
Cambridge, MD	1.52	1.70	1.62	1.87	1.87	2.35
Baltimore, MD	1.90	2.24	2.13	2.58	2.84	3.66
Annapolis, MD	1.75	2.03	1.95	2.34	2.54	3.28
Solomons Island, MD	1.37	1.47	1.44	1.59	1.63	1.89
Washington, DC	2.81	3.35	3.22	3.95	4.47	5.84
Sewells Point, VA	2.13	2.41	2.29	2.69	2.70	3.50
Chesapeake Bay Bridge Tunnel, VA	2.10	2.25	2.20	2.40	2.43	2.78

Table 22. Water levels for 1, 10, and 25 yr RP for SLC Scenario 3, Modified NRC-I.

SLC Scenario 3, Modified NRC-I						
	Water Level (m)–Datum: NAVD88					
	1 yr RP		10 yr RP		25 yr RP	
Station Name	Mean	90% CL	Mean	90% CL	Mean	90% CL
Eastport, ME	4.34	4.35	4.56	4.60	4.64	4.70
Bar Harbor, ME	2.80	2.81	3.09	3.13	3.20	3.26
Portland, ME	2.56	2.57	2.79	2.84	2.89	2.96
Boston, MA	2.70	2.71	2.98	3.04	3.09	3.19
Woods Hole, MA	1.34	1.35	1.83	2.02	2.10	2.41
Nantucket Island, MA	1.50	1.51	1.76	1.82	1.87	1.97
Newport, RI	1.64	1.65	2.08	2.23	2.32	2.58
Providence, RI	1.79	1.81	2.41	2.62	2.75	3.10
New London, CT	1.43	1.45	1.94	2.13	2.19	2.52
Montauk Point Light, NY	1.42	1.43	1.85	1.98	2.06	2.29
Kings Point, NY	2.37	2.40	3.07	3.32	3.43	3.85
The Battery, NY	1.86	1.88	2.25	2.39	2.45	2.70
Sandy Hook, NJ	2.06	2.08	2.50	2.67	2.72	3.02
Atlantic City, NJ	1.89	1.90	2.24	2.32	2.39	2.53
Cape May, NJ	1.97	1.98	2.22	2.27	2.30	2.37
Lewes, DE	1.78	1.79	2.11	2.18	2.25	2.37
Cambridge, MD	1.34	1.36	1.59	1.68	1.70	1.84
Baltimore, MD	1.37	1.39	1.74	1.91	1.94	2.22
Annapolis, MD	1.32	1.34	1.66	1.79	1.83	2.06
Solomons Island, MD	1.27	1.27	1.50	1.56	1.59	1.68
Washington, DC	1.57	1.59	2.25	2.50	2.63	3.04
Sewells Point, VA	1.66	1.68	2.05	2.18	2.22	2.44
Chesapeake Bay Bridge Tunnel, VA	1.79	1.80	2.14	2.22	2.27	2.40

Table 23. Water levels for 50, 100, and 500 yr RP for SLC Scenario 3, Modified NRC-I.

SLC Scenario 3, Modified NRC-I						
	Water Level (m)–Datum: NAVD88					
	50 yr RP		100 yr RP		500 yr RP	
Station Name	Mean	90% CL	Mean	90% CL	Mean	90% CL
Eastport, ME	4.71	4.79	4.77	4.88	4.93	5.13
Bar Harbor, ME	3.28	3.37	3.35	3.47	3.50	3.73
Portland, ME	2.96	3.08	3.04	3.20	3.24	3.55
Boston, MA	3.18	3.32	3.28	3.47	3.50	3.87
Woods Hole, MA	2.36	2.79	2.65	3.22	3.54	4.56
Nantucket Island, MA	1.96	2.11	2.05	2.25	2.27	2.67
Newport, RI	2.54	2.91	2.80	3.30	3.57	4.49
Providence, RI	3.07	3.57	3.43	4.11	4.53	5.76
New London, CT	2.42	2.90	2.66	3.35	3.36	4.71
Montauk Point Light, NY	2.24	2.59	2.44	2.94	2.96	4.02
Kings Point, NY	3.75	4.37	4.11	4.96	5.15	6.81
The Battery, NY	2.62	2.99	2.81	3.33	3.36	4.38
Sandy Hook, NJ	2.93	3.36	3.15	3.75	3.78	4.96
Atlantic City, NJ	2.51	2.72	2.64	2.92	2.97	3.52
Cape May, NJ	2.36	2.45	2.42	2.52	2.53	2.68
Lewes, DE	2.36	2.52	2.47	2.70	2.74	3.17
Cambridge, MD	1.79	2.00	1.88	2.17	2.12	2.67
Baltimore, MD	2.13	2.51	2.34	2.84	3.00	3.87
Annapolis, MD	2.00	2.32	2.18	2.62	2.74	3.54
Solomons Island, MD	1.67	1.80	1.75	1.92	1.93	2.25
Washington, DC	2.98	3.55	3.38	4.15	4.58	5.99
Sewells Point, VA	2.37	2.68	2.52	2.96	2.91	3.76
Chesapeake Bay Bridge Tunnel, VA	2.38	2.54	2.47	2.69	2.70	3.07

Table 24. Water levels for 1, 10, and 25 yr RP for SLC Scenario 4, Modified NRC-II.

SLC Scenario 4, Modified NRC-II						
	Water Level (m)–Datum: NAVD88					
	1 yr RP		10 yr RP		25 yr RP	
Station Name	Mean	90% CL	Mean	90% CL	Mean	90% CL
Eastport, ME	4.85	4.86	5.10	5.15	5.20	5.27
Bar Harbor, ME	3.20	3.21	3.63	3.68	3.77	3.84
Portland, ME	3.04	3.05	3.33	3.39	3.44	3.54
Boston, MA	3.17	3.18	3.50	3.57	3.63	3.74
Woods Hole, MA	1.87	1.90	2.35	2.58	2.61	2.98
Nantucket Island, MA	2.04	2.05	2.28	2.37	2.39	2.52
Newport, RI	2.17	2.19	2.59	2.78	2.81	3.13
Providence, RI	2.30	2.33	2.88	3.13	3.20	3.61
New London, CT	1.93	1.96	2.41	2.64	2.64	3.04
Montauk Point Light, NY	1.94	1.96	2.37	2.53	2.57	2.86
Kings Point, NY	2.84	2.87	3.48	3.75	3.80	4.27
The Battery, NY	2.35	2.37	2.71	2.88	2.89	3.19
Sandy Hook, NJ	2.57	2.59	2.98	3.18	3.18	3.53
Atlantic City, NJ	2.42	2.43	2.77	2.88	2.92	3.09
Cape May, NJ	2.50	2.51	2.75	2.81	2.83	2.91
Lewes, DE	2.29	2.30	2.62	2.71	2.75	2.89
Cambridge, MD	1.87	1.89	2.11	2.22	2.21	2.39
Baltimore, MD	1.90	1.92	2.24	2.46	2.42	2.77
Annapolis, MD	1.86	1.88	2.17	2.35	2.34	2.63
Solomons Island, MD	1.80	1.82	2.04	2.12	2.14	2.26
Washington, DC	2.03	2.06	2.64	2.93	2.97	3.44
Sewells Point, VA	2.17	2.20	2.54	2.69	2.70	2.96
Chesapeake Bay Bridge Tunnel, VA	2.32	2.34	2.66	2.76	2.79	2.94

Table 25. Water levels for 50, 100, and 500 yr RP for SLC Scenario 4, Modified NRC-II.

SLC Scenario 4, Modified NRC-II						
	Water Level (m)–Datum: NAVD88					
	50 yr RP		100 yr RP		500 yr RP	
Station Name	Mean	90% CL	Mean	90% CL	Mean	90% CL
Eastport, ME	5.27	5.37	5.35	5.47	5.51	5.74
Bar Harbor, ME	3.86	3.97	3.93	4.08	4.04	4.30
Portland, ME	3.53	3.66	3.62	3.80	3.80	4.16
Boston, MA	3.73	3.90	3.84	4.06	4.10	4.53
Woods Hole, MA	2.85	3.37	3.13	3.80	3.98	5.13
Nantucket Island, MA	2.47	2.66	2.55	2.81	2.76	3.24
Newport, RI	3.03	3.47	3.27	3.85	4.01	5.03
Providence, RI	3.50	4.07	3.84	4.60	4.88	6.20
New London, CT	2.85	3.42	3.07	3.86	3.71	5.20
Montauk Point Light, NY	2.75	3.18	2.94	3.55	3.46	4.68
Kings Point, NY	4.10	4.77	4.42	5.34	5.36	7.09
The Battery, NY	3.05	3.48	3.23	3.82	3.72	4.85
Sandy Hook, NJ	3.37	3.86	3.58	4.25	4.16	5.45
Atlantic City, NJ	3.05	3.29	3.18	3.51	3.51	4.15
Cape May, NJ	2.89	2.99	2.94	3.07	3.06	3.25
Lewes, DE	2.86	3.06	2.96	3.24	3.23	3.73
Cambridge, MD	2.29	2.56	2.38	2.74	2.60	3.26
Baltimore, MD	2.60	3.06	2.80	3.39	3.41	4.40
Annapolis, MD	2.49	2.90	2.67	3.20	3.18	4.11
Solomons Island, MD	2.22	2.39	2.30	2.52	2.49	2.90
Washington, DC	3.29	3.93	3.65	4.48	4.74	6.19
Sewells Point, VA	2.83	3.20	2.97	3.48	3.32	4.29
Chesapeake Bay Bridge Tunnel, VA	2.88	3.08	2.98	3.24	3.18	3.63

Table 26. Water levels for 1, 10, and 25 yr RP for SLC Scenario 5, Modified NRC-III.

SLC Scenario 5, Modified NRC-III						
	Water Level (m)–Datum: NAVD88					
	1yr RP		10 yr RP		25 yr RP	
Station Name	Mean	90% CL	Mean	90% CL	Mean	90% CL
Eastport, ME	5.38	5.39	5.68	5.73	5.79	5.86
Bar Harbor, ME	3.61	3.62	4.19	4.25	4.37	4.46
Portland, ME	3.54	3.55	3.91	3.97	4.03	4.14
Boston, MA	3.67	3.68	4.07	4.15	4.21	4.34
Woods Hole, MA	2.45	2.48	2.91	3.19	3.16	3.62
Nantucket Island, MA	2.61	2.62	2.85	2.95	2.95	3.12
Newport, RI	2.75	2.77	3.15	3.38	3.37	3.75
Providence, RI	2.87	2.90	3.42	3.71	3.72	4.20
New London, CT	2.49	2.53	2.94	3.23	3.16	3.64
Montauk Point Light, NY	2.51	2.53	2.93	3.13	3.13	3.48
Kings Point, NY	3.36	3.40	3.96	4.28	4.27	4.80
The Battery, NY	2.90	2.93	3.24	3.44	3.41	3.76
Sandy Hook, NJ	3.12	3.15	3.51	3.75	3.71	4.11
Atlantic City, NJ	2.99	3.01	3.34	3.47	3.49	3.70
Cape May, NJ	3.06	3.08	3.32	3.39	3.40	3.50
Lewes, DE	2.85	2.87	3.17	3.28	3.30	3.47
Cambridge, MD	2.44	2.46	2.67	2.81	2.76	2.99
Baltimore, MD	2.47	2.50	2.79	3.07	2.97	3.40
Annapolis, MD	2.43	2.46	2.74	2.96	2.89	3.26
Solomons Island, MD	2.38	2.39	2.62	2.72	2.72	2.87
Washington, DC	2.56	2.59	3.11	3.44	3.41	3.94
Sewells Point, VA	2.73	2.76	3.08	3.27	3.23	3.55
Chesapeake Bay Bridge Tunnel, VA	2.88	2.90	3.22	3.34	3.35	3.52

Table 27. Water levels for 50, 100, and 500 yr RP for SLC Scenario 5, Modified NRC-III.

SLC Scenario 5, Modified NRC-III						
	Water Level (m)–Datum: NAVD88					
	50 yr RP		100 yr RP		500 yr RP	
Station Name	Mean	90% CL	Mean	90% CL	Mean	90% CL
Eastport, ME	5.87	5.97	5.93	6.07	6.07	6.31
Bar Harbor, ME	4.49	4.61	4.58	4.75	4.73	5.03
Portland, ME	4.12	4.27	4.19	4.41	4.33	4.73
Boston, MA	4.31	4.50	4.41	4.66	4.58	5.06
Woods Hole, MA	3.40	4.01	3.67	4.46	4.51	5.80
Nantucket Island, MA	3.03	3.26	3.11	3.43	3.31	3.88
Newport, RI	3.57	4.09	3.81	4.48	4.53	5.68
Providence, RI	4.00	4.66	4.33	5.18	5.33	6.77
New London, CT	3.36	4.03	3.57	4.48	4.16	5.83
Montauk Point Light, NY	3.30	3.82	3.49	4.21	4.00	5.41
Kings Point, NY	4.55	5.29	4.85	5.86	5.74	7.59
The Battery, NY	3.56	4.06	3.72	4.40	4.19	5.46
Sandy Hook, NJ	3.89	4.45	4.08	4.85	4.63	6.06
Atlantic City, NJ	3.62	3.91	3.75	4.15	4.08	4.82
Cape May, NJ	3.46	3.58	3.51	3.66	3.63	3.85
Lewes, DE	3.41	3.64	3.51	3.83	3.76	4.35
Cambridge, MD	2.85	3.17	2.93	3.37	3.14	3.94
Baltimore, MD	3.14	3.70	3.33	4.04	3.91	5.05
Annapolis, MD	3.04	3.54	3.21	3.85	3.72	4.80
Solomons Island, MD	2.80	3.01	2.88	3.16	3.08	3.58
Washington, DC	3.69	4.41	4.02	4.94	5.01	6.55
Sewells Point, VA	3.36	3.80	3.49	4.09	3.81	4.93
Chesapeake Bay Bridge Tunnel, VA	3.44	3.68	3.53	3.84	3.73	4.25

Table 28. Water levels for 1, 10, and 25 yr RP for SLC Scenario 6, NOAA Highest.

SLC Scenario 6, NOAA Highest						
	Water Level (m)–Datum: NAVD88					
	1 yr RP		10 yr RP		25 yr RP	
Station Name	Mean	90% CL	Mean	90% CL	Mean	90% CL
Eastport, ME	5.91	5.92	6.27	6.32	6.39	6.47
Bar Harbor, ME	4.03	4.04	4.76	4.82	4.98	5.08
Portland, ME	4.05	4.06	4.49	4.57	4.63	4.76
Boston, MA	4.18	4.19	4.65	4.74	4.80	4.95
Woods Hole, MA	3.04	3.07	3.49	3.83	3.74	4.28
Nantucket Island, MA	3.20	3.22	3.44	3.56	3.54	3.73
Newport, RI	3.33	3.36	3.73	4.00	3.94	4.39
Providence, RI	3.45	3.48	3.98	4.32	4.28	4.83
New London, CT	3.08	3.12	3.51	3.84	3.72	4.27
Montauk Point Light, NY	3.09	3.12	3.51	3.75	3.71	4.12
Kings Point, NY	3.89	3.93	4.49	4.85	4.80	5.39
The Battery, NY	3.47	3.50	3.80	4.04	3.96	4.36
Sandy Hook, NJ	3.70	3.73	4.08	4.35	4.27	4.73
Atlantic City, NJ	3.57	3.59	3.93	4.07	4.08	4.32
Cape May, NJ	3.65	3.67	3.90	3.98	3.98	4.10
Lewes, DE	3.43	3.45	3.74	3.87	3.87	4.08
Cambridge, MD	3.02	3.05	3.25	3.42	3.34	3.62
Baltimore, MD	3.05	3.09	3.37	3.71	3.54	4.05
Annapolis, MD	3.02	3.05	3.32	3.59	3.47	3.91
Solomons Island, MD	2.96	2.98	3.21	3.33	3.31	3.50
Washington, DC	3.11	3.15	3.62	4.01	3.90	4.51
Sewells Point, VA	3.30	3.34	3.65	3.87	3.80	4.16
Chesapeake Bay Bridge Tunnel, VA	3.47	3.49	3.80	3.94	3.92	4.13

Table 29. Water levels for 50, 100, and 500 yr RP for SLC Scenario 6, NOAA Highest.

SLC Scenario 6, NOAA Highest						
	Water Level (m)–Datum: NAVD88					
	50 yr RP		100 yr RP		500 yr RP	
Station Name	Mean	90% CL	Mean	90% CL	Mean	90% CL
Eastport, ME	6.47	6.58	6.54	6.69	6.65	6.91
Bar Harbor, ME	5.13	5.27	5.25	5.44	5.44	5.79
Portland, ME	4.73	4.91	4.81	5.05	4.93	5.40
Boston, MA	4.91	5.12	4.99	5.28	5.13	5.66
Woods Hole, MA	3.98	4.69	4.25	5.15	5.07	6.52
Nantucket Island, MA	3.62	3.89	3.70	4.06	3.89	4.56
Newport, RI	4.15	4.75	4.38	5.15	5.09	6.38
Providence, RI	4.55	5.29	4.87	5.83	5.85	7.43
New London, CT	3.90	4.68	4.11	5.15	4.67	6.54
Montauk Point Light, NY	3.88	4.48	4.07	4.90	4.57	6.18
Kings Point, NY	5.08	5.90	5.38	6.49	6.26	8.28
The Battery, NY	4.10	4.68	4.26	5.03	4.70	6.12
Sandy Hook, NJ	4.44	5.08	4.62	5.50	5.16	6.75
Atlantic City, NJ	4.21	4.54	4.34	4.79	4.67	5.52
Cape May, NJ	4.05	4.19	4.10	4.27	4.22	4.48
Lewes, DE	3.98	4.25	4.08	4.45	4.33	5.00
Cambridge, MD	3.42	3.81	3.50	4.03	3.70	4.65
Baltimore, MD	3.70	4.37	3.89	4.72	4.47	5.76
Annapolis, MD	3.62	4.21	3.79	4.54	4.28	5.53
Solomons Island, MD	3.39	3.65	3.47	3.81	3.67	4.27
Washington, DC	4.17	4.98	4.47	5.50	5.40	7.06
Sewells Point, VA	3.92	4.43	4.04	4.74	4.35	5.62
Chesapeake Bay Bridge Tunnel, VA	4.02	4.29	4.11	4.46	4.30	4.90

5.3 Comparison between MCLC simulation and linear superposition of SLC scenarios

In the methodology presented in this report, the SLC component is integrated with extreme water levels using time-dependant MCLC approach. For each of the deterministic future SLC scenarios, the SLC is progressively added as a function of time (year after year) to randomly sampled astronomical tide and storm surge components, starting at preset and ending when the sought future horizon is reached (e.g., 2064, 2114).

An alternate approach is the linear superposition of the SLC component to the historical water levels. This approach is equivalent to shifting the vertical datum up to the expected sea level dictated by each of the different SLC scenarios. Here, the vertical datum shift represents an adjustment from present conditions to the end year of a given future horizon. This staircase approach, with no time progression, results in more conservative projects compared to the MCLC approach. The differences between both approaches' 100 yr water levels are listed in Tables 30–32 for SLC Scenarios 2 through 6.

Given the high uncertainty associated with the deterministic SLC scenarios, the MLCS approach could be better suited for projects where risk due to rising sea levels could be reassessed at some reasonably short time in the future. Conversely, linear superposition (staircase) approach would be better suited for critical areas or infrastructure where conservative projections of extreme water levels are preferable.

Table 30. Comparison of MCLC vs. linear superposition of SLC Scenarios 2 and 3.

100 yr Water Level (m, NAVD88)						
	Scenario 2: Historical (Linear)			Scenario 3: Modified NRC-I		
Station Name	MCLC	Linear Superposition	Diff	MCLC	Linear Superposition	Diff
Eastport, ME	4.47	4.54	0.08	4.77	4.93	0.16
Bar Harbor, ME	3.02	3.11	0.09	3.35	3.50	0.15
Portland, ME	2.77	2.85	0.08	3.04	3.23	0.19
Boston, MA	3.02	3.13	0.11	3.28	3.52	0.25
Woods Hole, MA	2.41	2.51	0.11	2.65	2.90	0.25
Nantucket Island, MA	1.78	1.89	0.11	2.05	2.28	0.23
Newport, RI	2.55	2.65	0.10	2.80	3.04	0.24
Providence, RI	3.23	3.32	0.09	3.43	3.71	0.28
New London, CT	2.45	2.55	0.10	2.66	2.94	0.28
Montauk Point Light, NY	2.17	2.28	0.11	2.44	2.67	0.24
Kings Point, NY	3.96	4.07	0.12	4.11	4.46	0.35
The Battery, NY	2.60	2.72	0.13	2.81	3.11	0.30
Sandy Hook, NJ	2.92	3.09	0.16	3.15	3.47	0.33
Atlantic City, NJ	2.34	2.46	0.12	2.64	2.85	0.21
Cape May, NJ	2.12	2.25	0.13	2.42	2.64	0.22
Lewes, DE	2.20	2.33	0.13	2.47	2.71	0.25
Cambridge, MD	1.62	1.75	0.13	1.88	2.14	0.26
Baltimore, MD	2.13	2.26	0.13	2.34	2.65	0.31
Annapolis, MD	1.95	2.09	0.14	2.18	2.48	0.29
Solomons Island, MD	1.44	1.55	0.11	1.75	1.94	0.19
Washington, DC	3.22	3.37	0.15	3.38	3.76	0.38
Sewells Point, VA	2.29	2.46	0.17	2.52	2.85	0.33
Chesapeake Bay Bridge Tunnel, VA	2.20	2.38	0.18	2.47	2.77	0.29

Table 31. Comparison of MCLC vs. linear superposition of SLC Scenarios 4 and 5.

100 yr Water Level (m, NAVD88)						
	Scenario 4: Modified NRC-II			Scenario 5: Modified NRC-III		
Station Name	MCLC	Linear Superposition	Diff	MCLC	Linear Superposition	Diff
Eastport, ME	5.35	5.55	0.20	5.93	6.16	0.23
Bar Harbor, ME	3.93	4.11	0.18	4.58	4.72	0.14
Portland, ME	3.62	3.85	0.23	4.19	4.46	0.27
Boston, MA	3.84	4.14	0.29	4.41	4.75	0.34
Woods Hole, MA	3.13	3.51	0.38	3.67	4.13	0.46
Nantucket Island, MA	2.55	2.89	0.33	3.11	3.50	0.39
Newport, RI	3.27	3.65	0.38	3.81	4.27	0.46
Providence, RI	3.84	4.32	0.48	4.33	4.94	0.61
New London, CT	3.07	3.55	0.48	3.57	4.17	0.60
Montauk Point Light, NY	2.94	3.29	0.35	3.49	3.90	0.41
Kings Point, NY	4.42	5.07	0.65	4.85	5.69	0.84
The Battery, NY	3.23	3.73	0.50	3.72	4.34	0.62
Sandy Hook, NJ	3.58	4.09	0.51	4.08	4.70	0.62
Atlantic City, NJ	3.18	3.46	0.29	3.75	4.08	0.33
Cape May, NJ	2.94	3.25	0.31	3.51	3.87	0.35
Lewes, DE	2.96	3.33	0.36	3.51	3.94	0.43
Cambridge, MD	2.38	2.76	0.38	2.93	3.37	0.44
Baltimore, MD	2.80	3.27	0.47	3.33	3.88	0.55
Annapolis, MD	2.67	3.09	0.43	3.21	3.71	0.49
Solomons Island, MD	2.30	2.55	0.26	2.88	3.17	0.29
Washington, DC	3.65	4.37	0.72	4.02	4.98	0.96
Sewells Point, VA	2.97	3.46	0.50	3.49	4.08	0.59
Chesapeake Bay Bridge Tunnel, VA	2.98	3.38	0.40	3.53	4.00	0.47

Table 32. Comparison of MCLC vs. linear superposition of SLC Scenario 6.

100 yr Water Level (m, NAVD88)			
	Scenario 6: NOAA Highest		
Station Name	MCLC	Linear Superposition	Diff
Eastport, ME	6.54	6.78	0.24
Bar Harbor, ME	5.25	5.34	0.09
Portland, ME	4.81	5.08	0.27
Boston, MA	4.99	5.36	0.37
Woods Hole, MA	4.25	4.74	0.50
Nantucket Island, MA	3.70	4.12	0.42
Newport, RI	4.38	4.88	0.51
Providence, RI	4.87	5.55	0.68
New London, CT	4.11	4.78	0.68
Montauk Point Light, NY	4.07	4.52	0.45
Kings Point, NY	5.38	6.30	0.92
The Battery, NY	4.26	4.96	0.70
Sandy Hook, NJ	4.62	5.32	0.69
Atlantic City, NJ	4.34	4.69	0.35
Cape May, NJ	4.10	4.48	0.38
Lewes, DE	4.08	4.56	0.48
Cambridge, MD	3.50	3.99	0.48
Baltimore, MD	3.89	4.50	0.60
Annapolis, MD	3.79	4.32	0.53
Solomons Island, MD	3.47	3.78	0.31
Washington, DC	4.47	5.60	1.12
Sewells Point, VA	4.04	4.69	0.65
Chesapeake Bay Bridge Tunnel, VA	4.11	4.61	0.51

6 Conclusions

The study summarized in this report is focused on providing statistical analysis of historical, regional, storm-induced water level responses to support the North Atlantic Comprehensive Coastal Study (NACCS). The main objective of this effort is to obtain first-order estimates of storm-induced water level statistics at locations along the U.S. North Atlantic coast to support posthurricane Sandy coastal planning studies. The study also includes forecasting of future storm water levels based on the historical range of tidal elevations and potential sea level change scenarios.

Statistics were computed based solely on verified hourly water level measurements acquired from National Oceanic and Atmospheric Administration's (NOAA) website and complemented by NOAA's monthly maximum water level records, excluding any kind of high-resolution hydrodynamic modeling. In this simplified analysis, tropical and extratropical storms were treated as a single population. A separate NACCS study is focused on developing high-fidelity extremal statistics of water levels using high-fidelity numerical hydrodynamic modeling with more sophisticated multiparameter statistical analysis.

This study utilized water level measurements from 23 NOAA National Ocean Service (NOS) water level gages spanning the northeast coast from Virginia to Maine. The criteria for selecting these gages were coastal location, minimum of 30 year (yr) continuous record length, and modern instrumentation. Records were backfilled with missing storms through coordination with NOAA NOS. Each record was analyzed with peaks-over-threshold censoring analysis to define storms, and the partial duration series were fit to a generalized Pareto distribution (GPD). The record of each gage was extended to a length of 100 yr through Monte Carlo Life-Cycle simulation. The final 100 yr return period water levels were favorably compared to those published by NOAA.

The 23 100 yr water level records were superimposed with bootstrap sampled tides and 6 different sea level change scenarios. This was done for a total of 10,000 realizations of 100 yr life cycles. For each of the 23 gages, the mean extremal GPD was computed along with 10% and 90% CL. The results are given as tabulated specific return period water levels, as well as water level versus return period plots.

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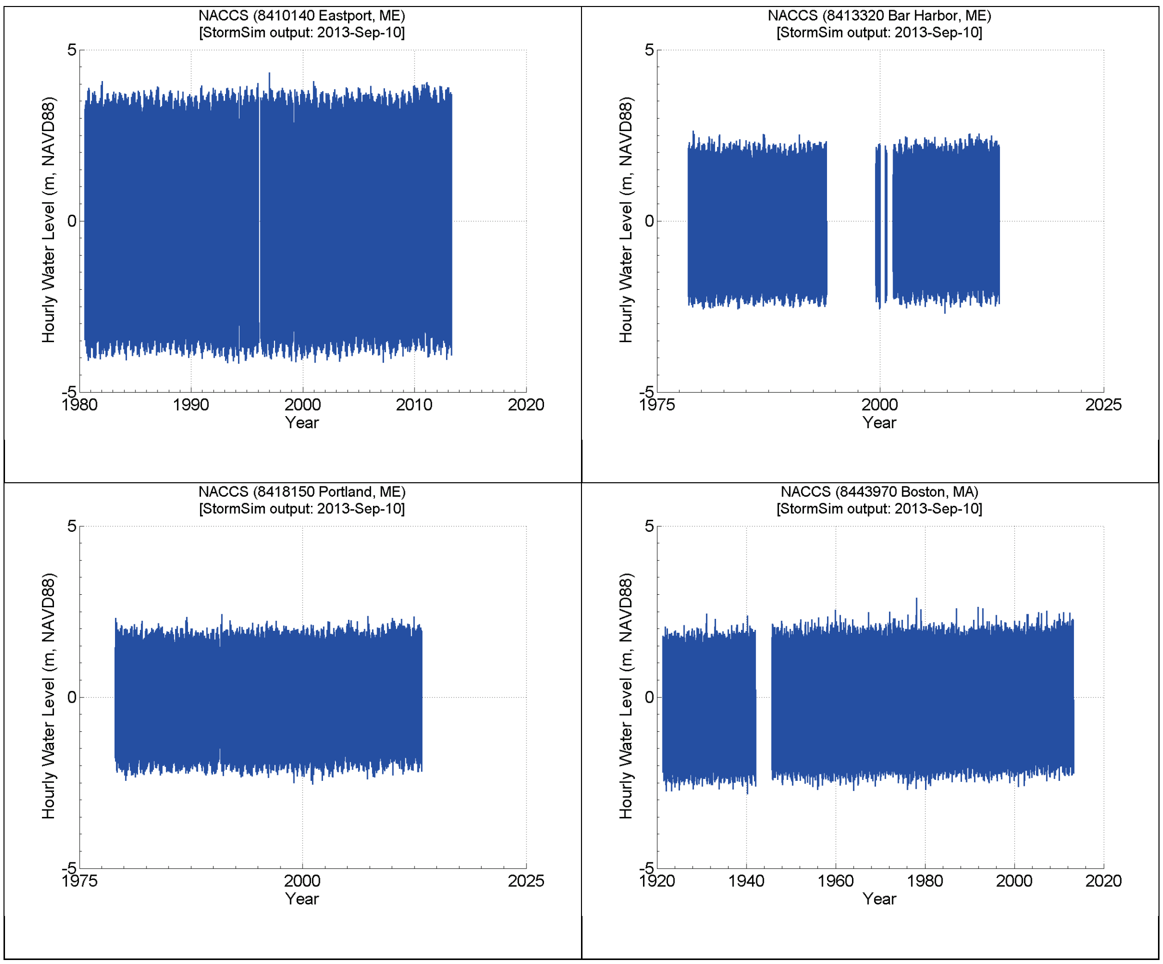
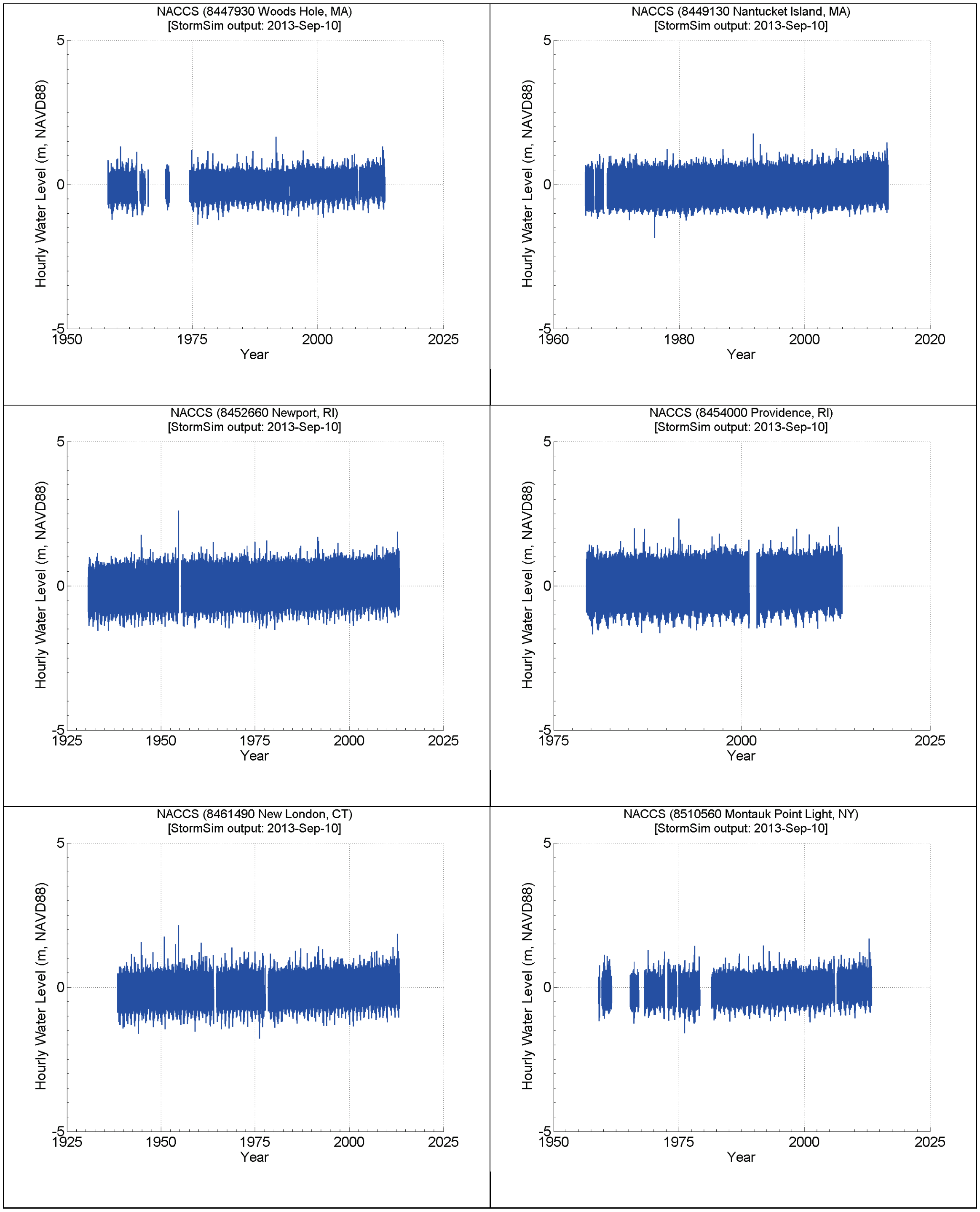
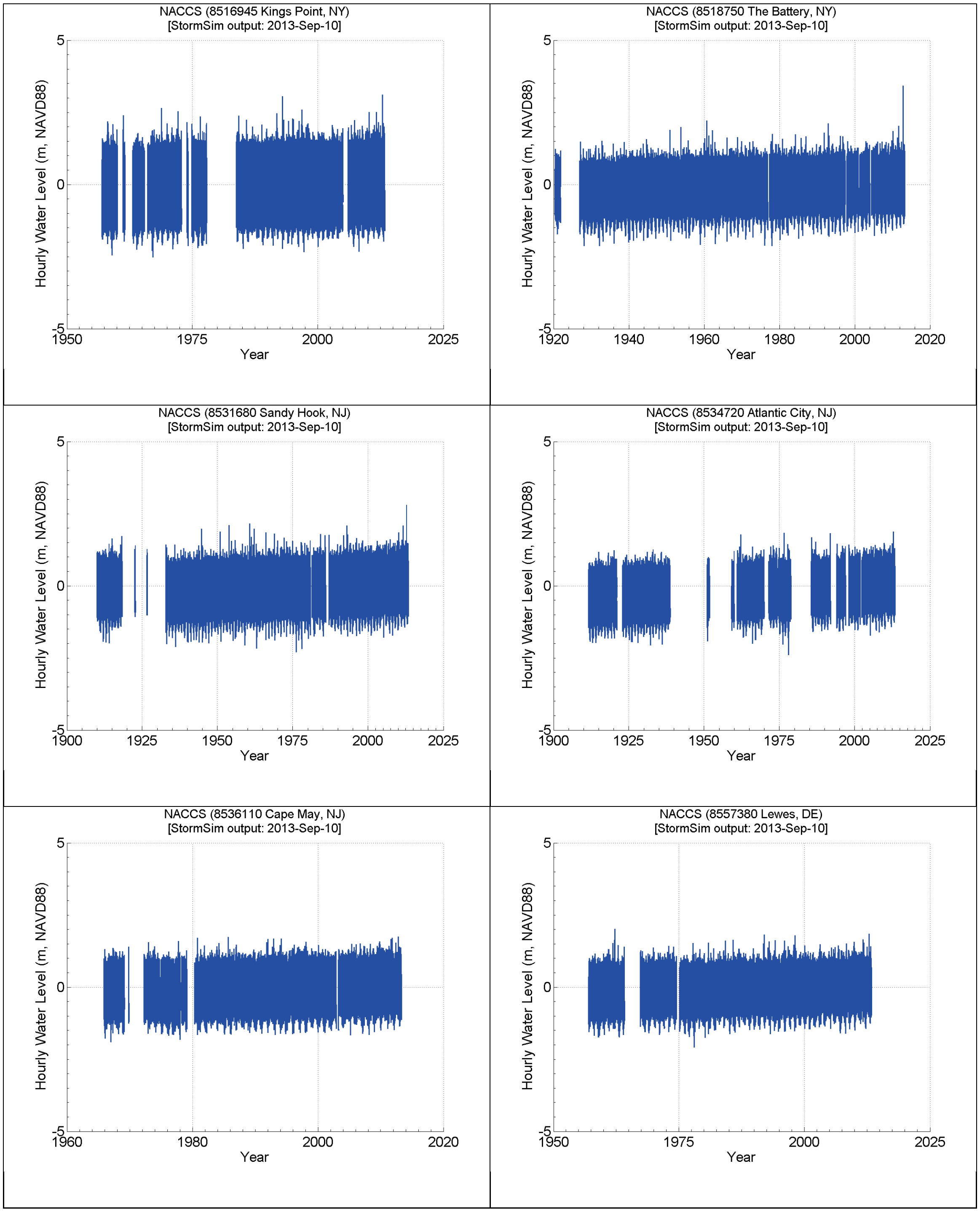
Appendix A: Water Level Measurements

Measured hourly water level data

The following pages present time series of hourly water level measurements for the 23 gages listed in Table 1.




NACCS (8447930 Woods Hole, MA)
[StormSim output: 2013-Sep-10]
Hourly Water Level (m, NAVD88)
Year
NACCS (8449130 Nantucket Island, MA)
[StormSim output: 2013-Sep-10]
Hourly Water Level (m, NAVD88)
Year
NACCS (8452660 Newport, RI)
[StormSim output: 2013-Sep-10]
Hourly Water Level (m, NAVD88)
Year
NACCS (8454000 Providence, RI)
[StormSim output: 2013-Sep-10]
Hourly Water Level (m, NAVD88)
Year
NACCS (8461490 New London, CT)
[StormSim output: 2013-Sep-10]
Hourly Water Level (m, NAVD88)
Year
NACCS (8510560 Montauk Point Light, NY)
[StormSim output: 2013-Sep-10]
Hourly Water Level (m, NAVD88)
Year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Hourly Water Level (m, NAVD88)
Year
NACCS (8518750 The Battery, NY)
[StormSim output: 2013-Sep-10]
Hourly Water Level (m, NAVD88)
Year
NACCS (8531680 Sandy Hook, NJ)
[StormSim output: 2013-Sep-10]
Hourly Water Level (m, NAVD88)
Year
NACCS (8534720 Atlantic City, NJ)
[StormSim output: 2013-Sep-10]
Hourly Water Level (m, NAVD88)
Year
NACCS (8536110 Cape May, NJ)
[StormSim output: 2013-Sep-10]
Hourly Water Level (m, NAVD88)
Year
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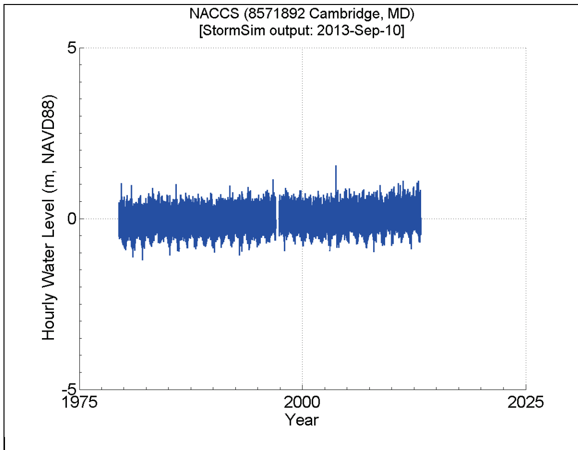
Hourly Water Level (m, NAVD88)
Year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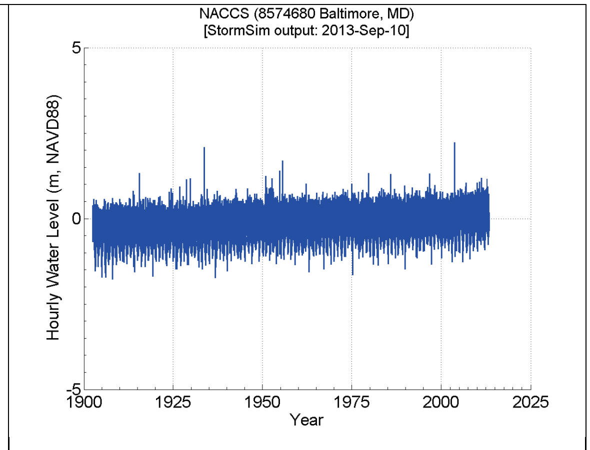
Hourly Water Level (m, NAVD88)
Year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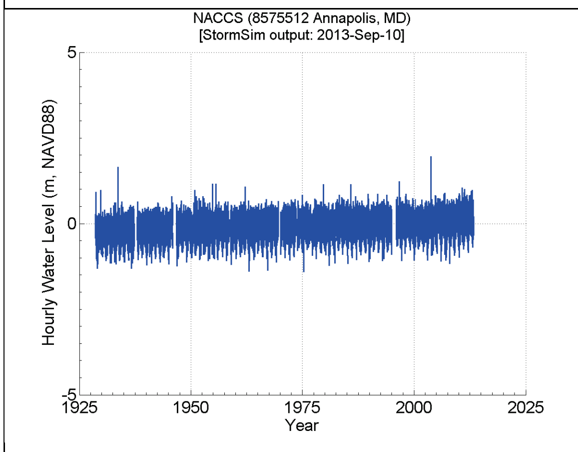
Hourly Water Level (m, NAVD88)
Year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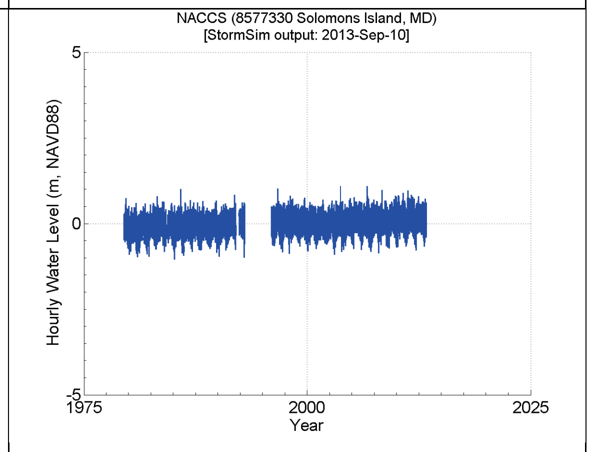
Hourly Water Level (m, NAVD88)
Year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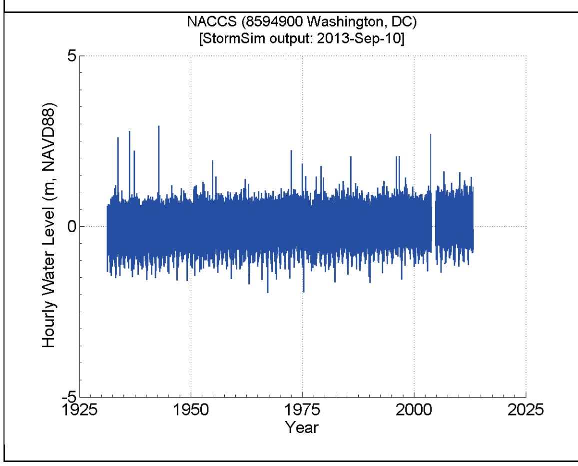
Hourly Water Level (m, NAVD88)
Year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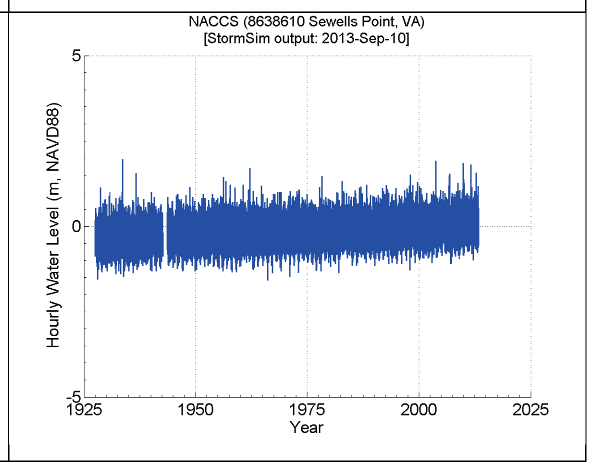
Hourly Water Level (m, NAVD88)
Year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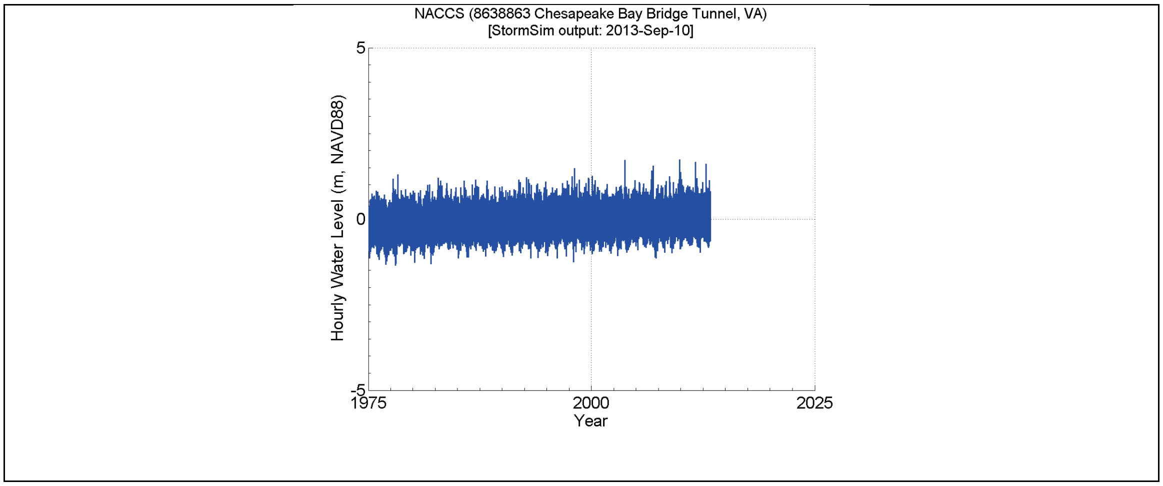
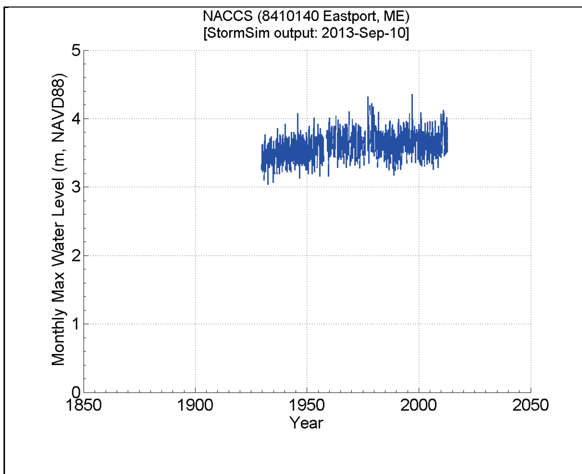
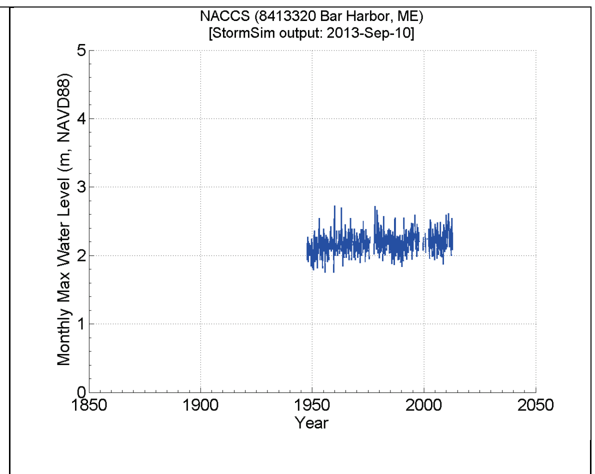
Hourly Water Level (m, NAVD88)
Year

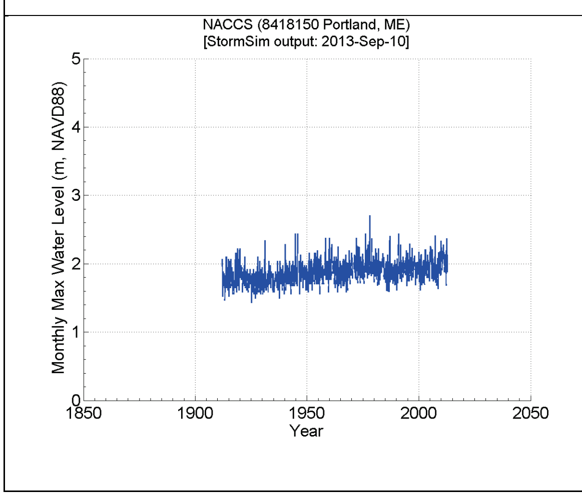


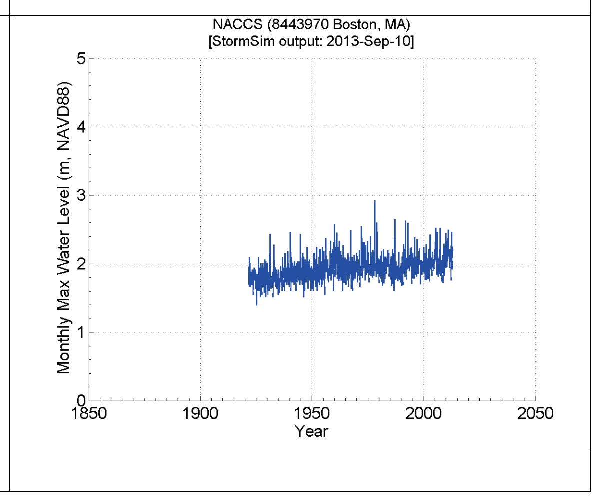
Measured monthly maximum water level data

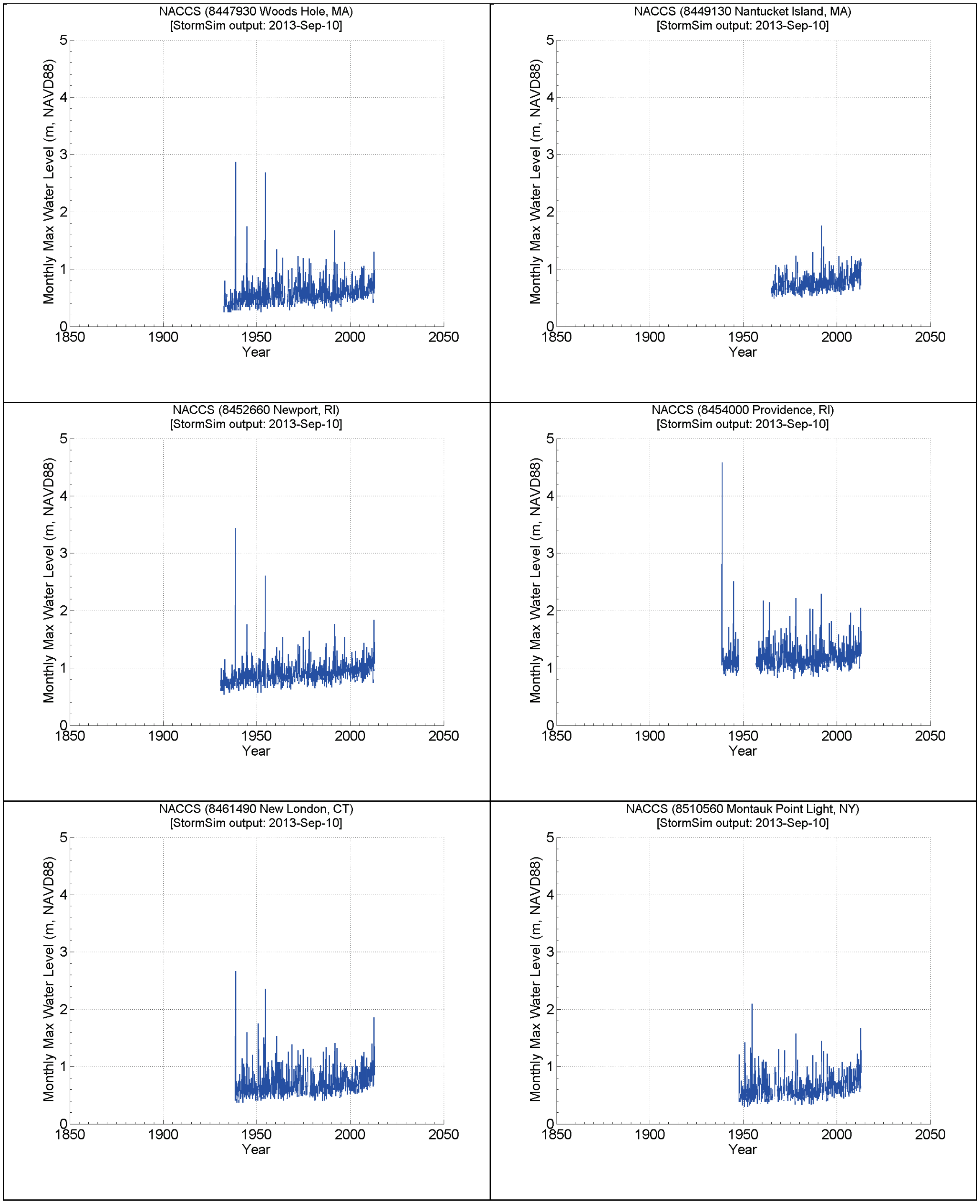
The following pages present monthly maximum series of water level measurements for the 23 gages listed in Table 1.

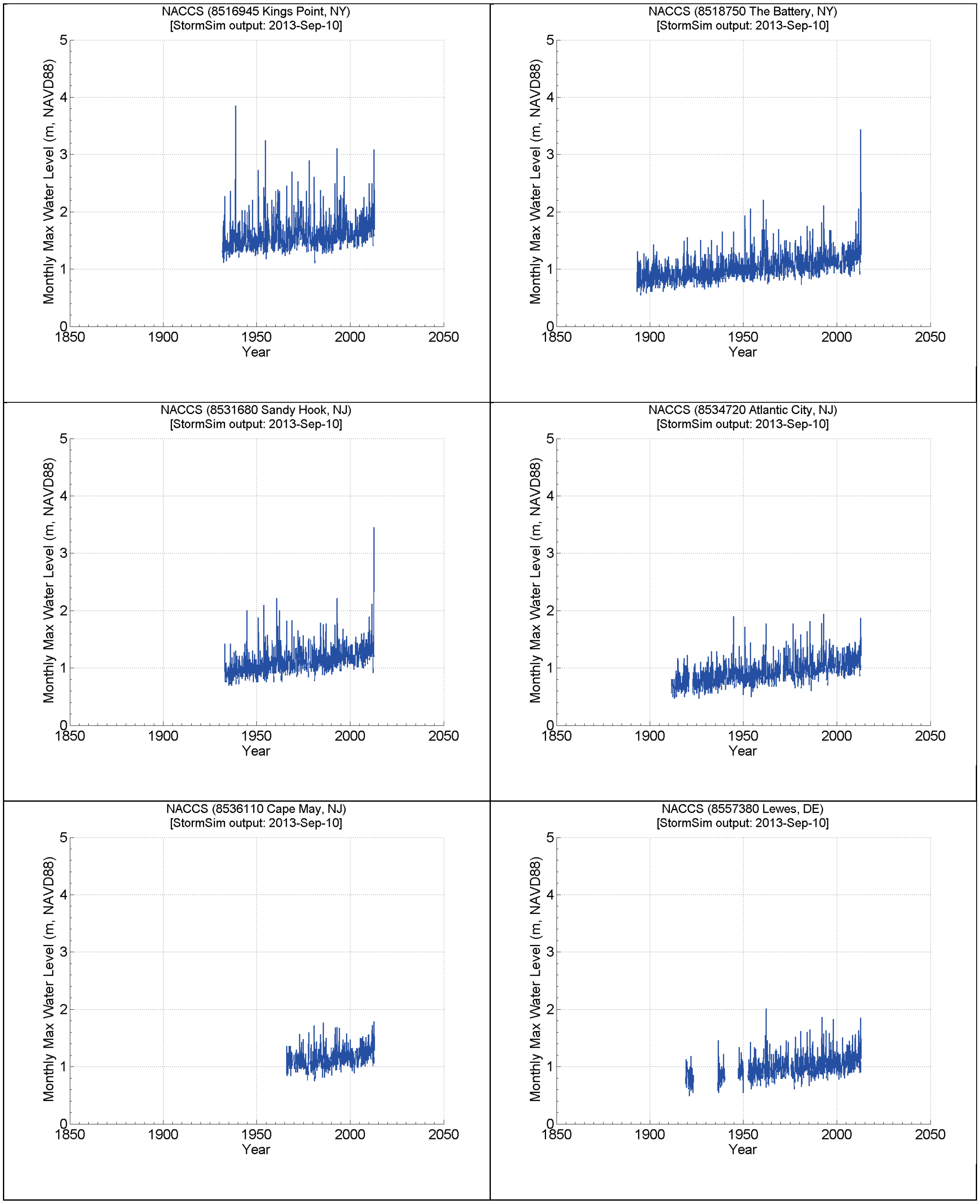


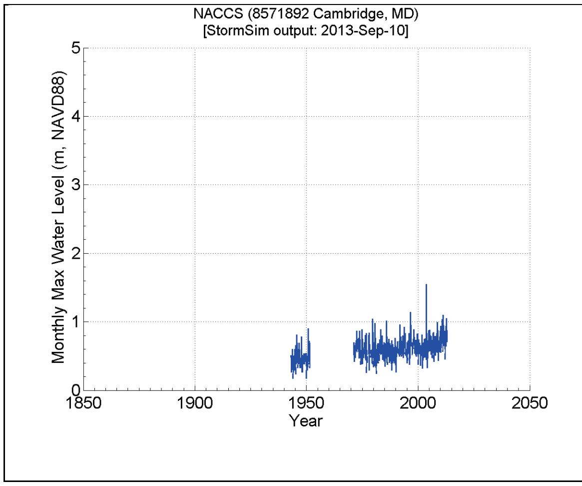


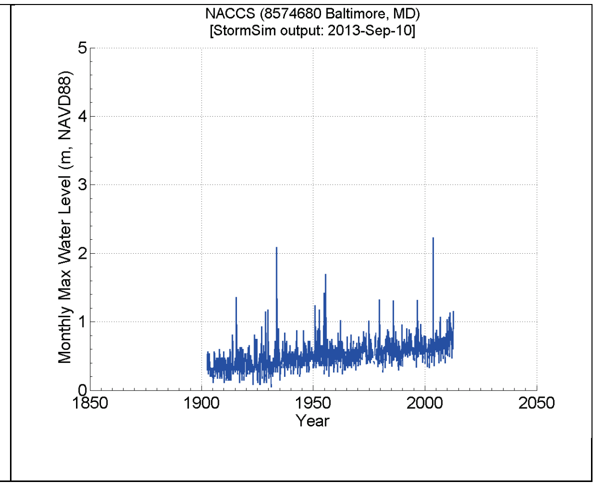


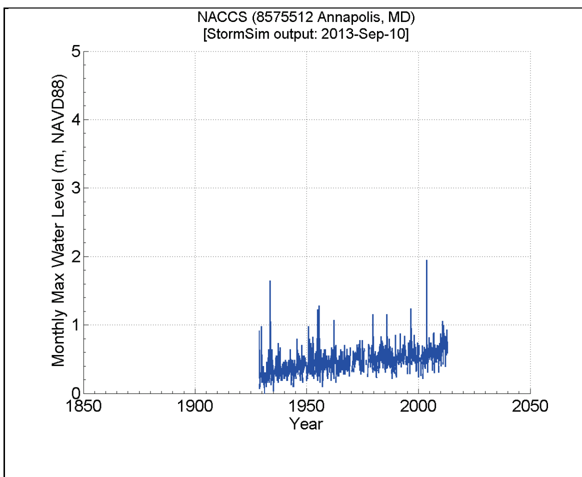


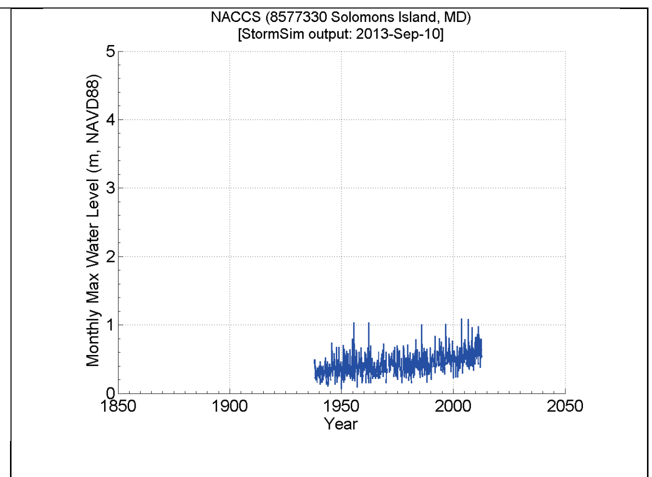

NACCS (8447930 Woods Hole, MA)
[StormSim output: 2013-Sep-10]
NACCS (8449130 Nantucket Island, MA)
[StormSim output: 2013-Sep-10]
NACCS (8452660 Newport, RI)
[StormSim output: 2013-Sep-10]
NACCS (8454000 Providence, RI)
[StormSim output: 2013-Sep-10]
NACCS (8461490 New London, CT)
[StormSim output: 2013-Sep-10]
NACCS (8510560 Montauk Point Light, NY)
[StormSim output: 2013-Sep-10]
Monthly Max Water Level (m, NAVD88)
Year
0
1
2
3
4
5
1850
1900
1950
2000
2050

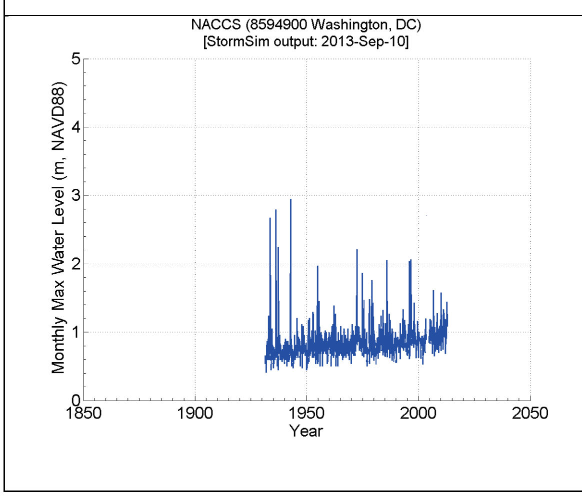

NACCS (8516945 Kings Point, NY)
[StormSim output: 2013-Sep-10]
NACCS (8518750 The Battery, NY)
[StormSim output: 2013-Sep-10]
NACCS (8531680 Sandy Hook, NJ)
[StormSim output: 2013-Sep-10]
NACCS (8534720 Atlantic City, NJ)
[StormSim output: 2013-Sep-10]
NACCS (8536110 Cape May, NJ)
[StormSim output: 2013-Sep-10]
NACCS (8557380 Lewes, DE)
[StormSim output: 2013-Sep-10]
Monthly Max Water Level (m, NAVD88)
Year
0
1
2
3
4
5
1850
1900
1950
2000
2050

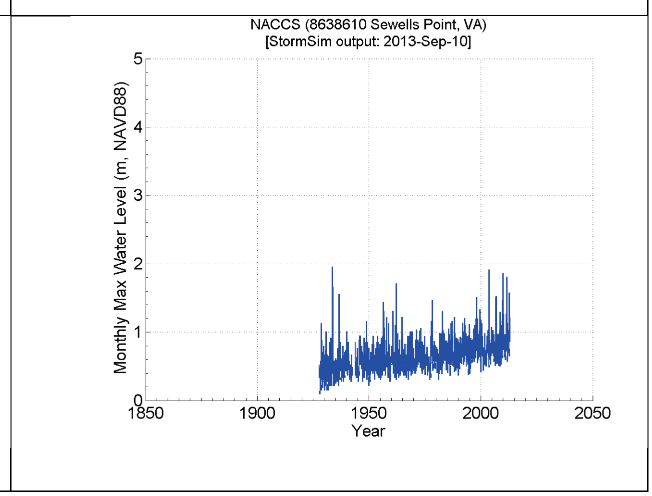

NACCS (8571892 Cambridge, MD)
[StormSim output: 2013-Sep-10]
Monthly Max Water Level (m, NAVD88)
Year
0
1
2
3
4
5
1850
1900
1950
2000
2050

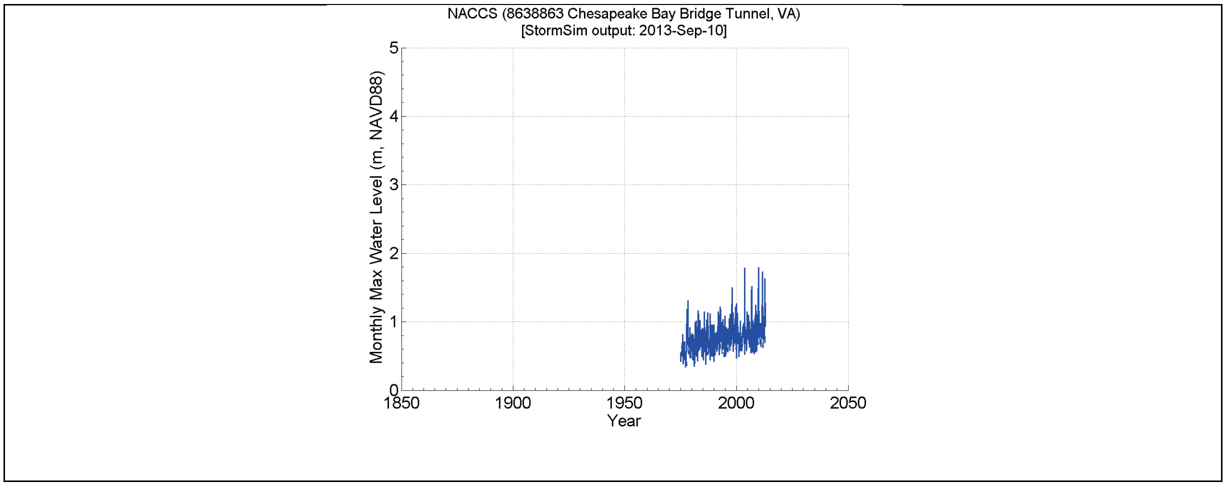

NACCS (8574680 Baltimore, MD)
[StormSim output: 2013-Sep-10]
Monthly Max Water Level (m, NAVD88)
Year
0
1
2
3
4
5
1850
1900
1950
2000
2050


NACCS (8575512 Annapolis, MD)
[StormSim output: 2013-Sep-10]
Monthly Max Water Level (m, NAVD88)
Year
0
1
2
3
4
5
1850
1900
1950
2000
2050


NACCS (8577330 Solomons Island, MD)
[StormSim output: 2013-Sep-10]
Monthly Max Water Level (m, NAVD88)
Year
0
1
2
3
4
5
1850
1900
1950
2000
2050


NACCS (8594900 Washington, DC)
[StormSim output: 2013-Sep-10]
Monthly Max Water Level (m, NAVD88)
Year
0
1
2
3
4
5
1850
1900
1950
2000
2050

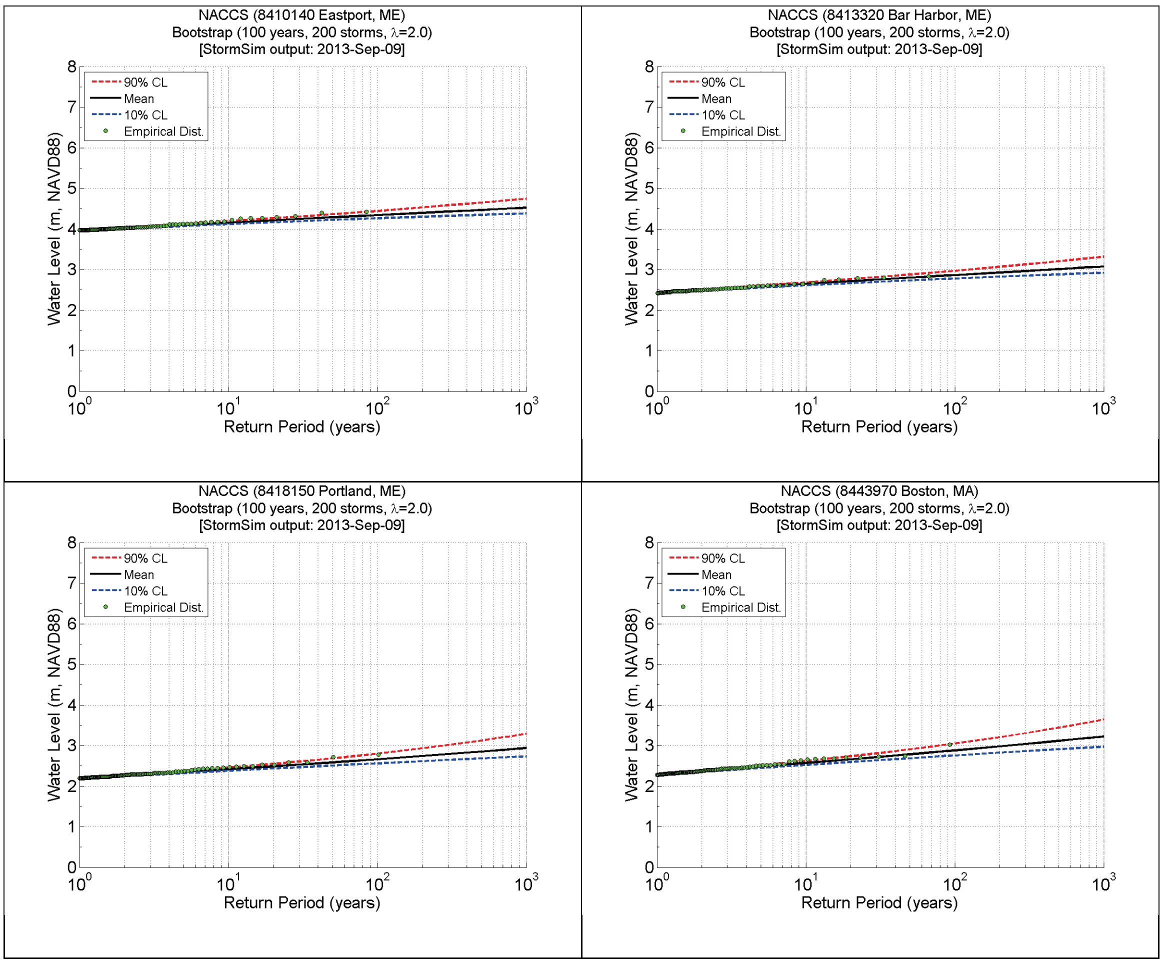

NACCS (8638610 Sewells Point, VA)
[StormSim output: 2013-Sep-10]
Monthly Max Water Level (m, NAVD88)
Year
0
1
2
3
4
5
1850
1900
1950
2000
2050

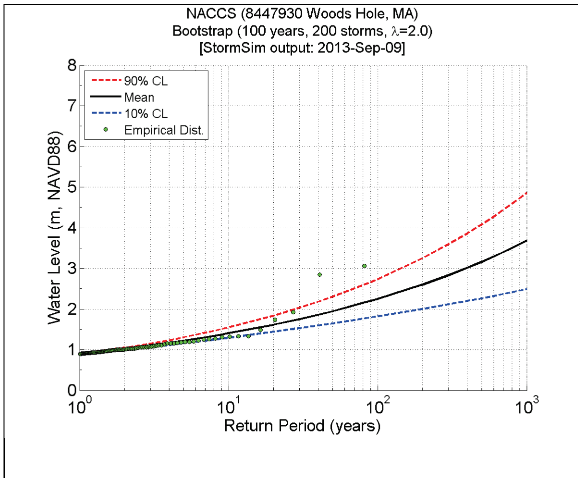

NACCS (8638863 Chesapeake Bay Bridge Tunnel, VA)
[StormSim output: 2013-Sep-10]
Monthly Max Water Level (m, NAVD88)
0
1
2
3
4
5
1850
1900
1950
2000
2050
Year

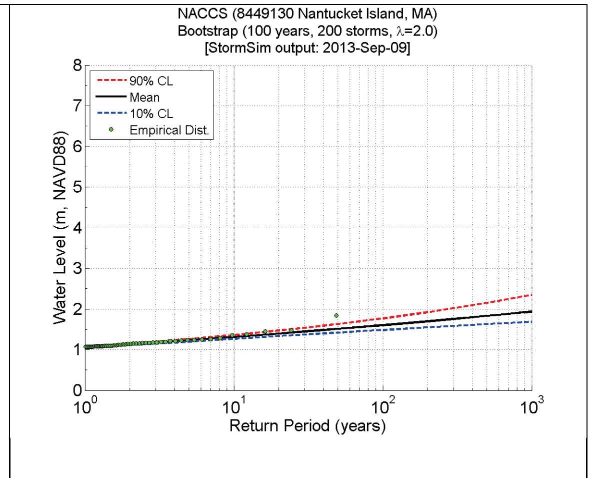
Appendix B: Historical Extreme Water Levels

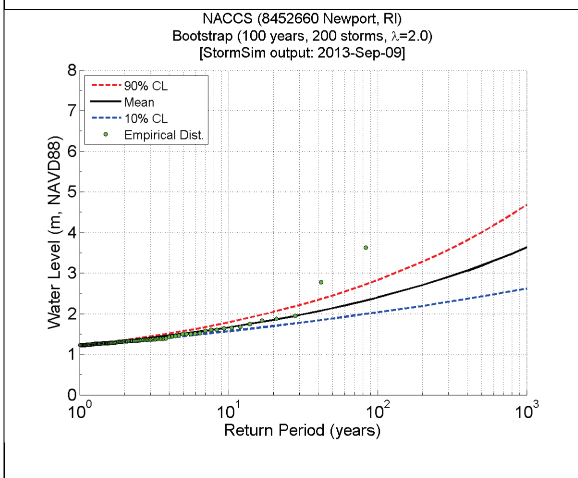
Statistical analysis of historical extreme water levels

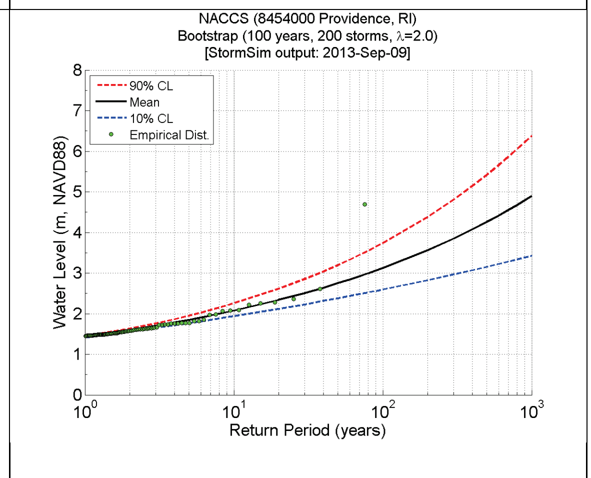
The following pages present the return period plots resulting from the statistical analysis of extreme water levels.

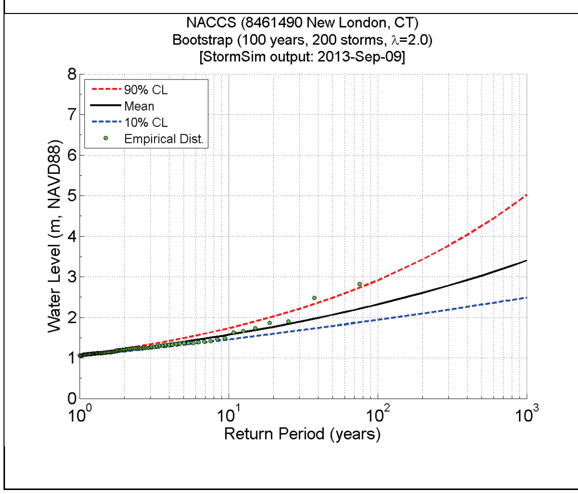


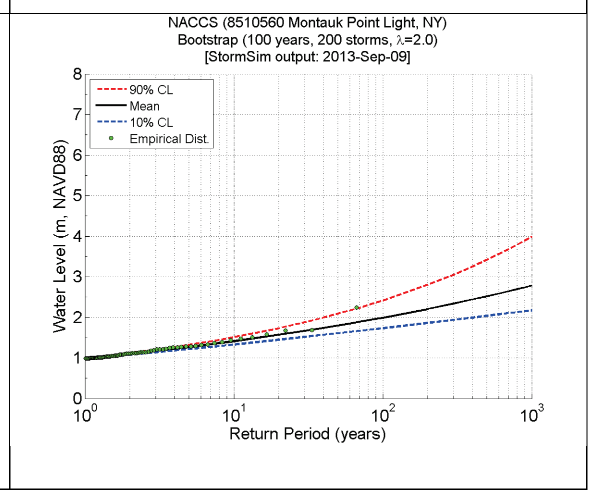

NACCS (8447930 Woods Hole, MA)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
90% CL
Mean
10% CL
Empirical Dist.
Water Level (m, NAVD88)
Return Period (years)

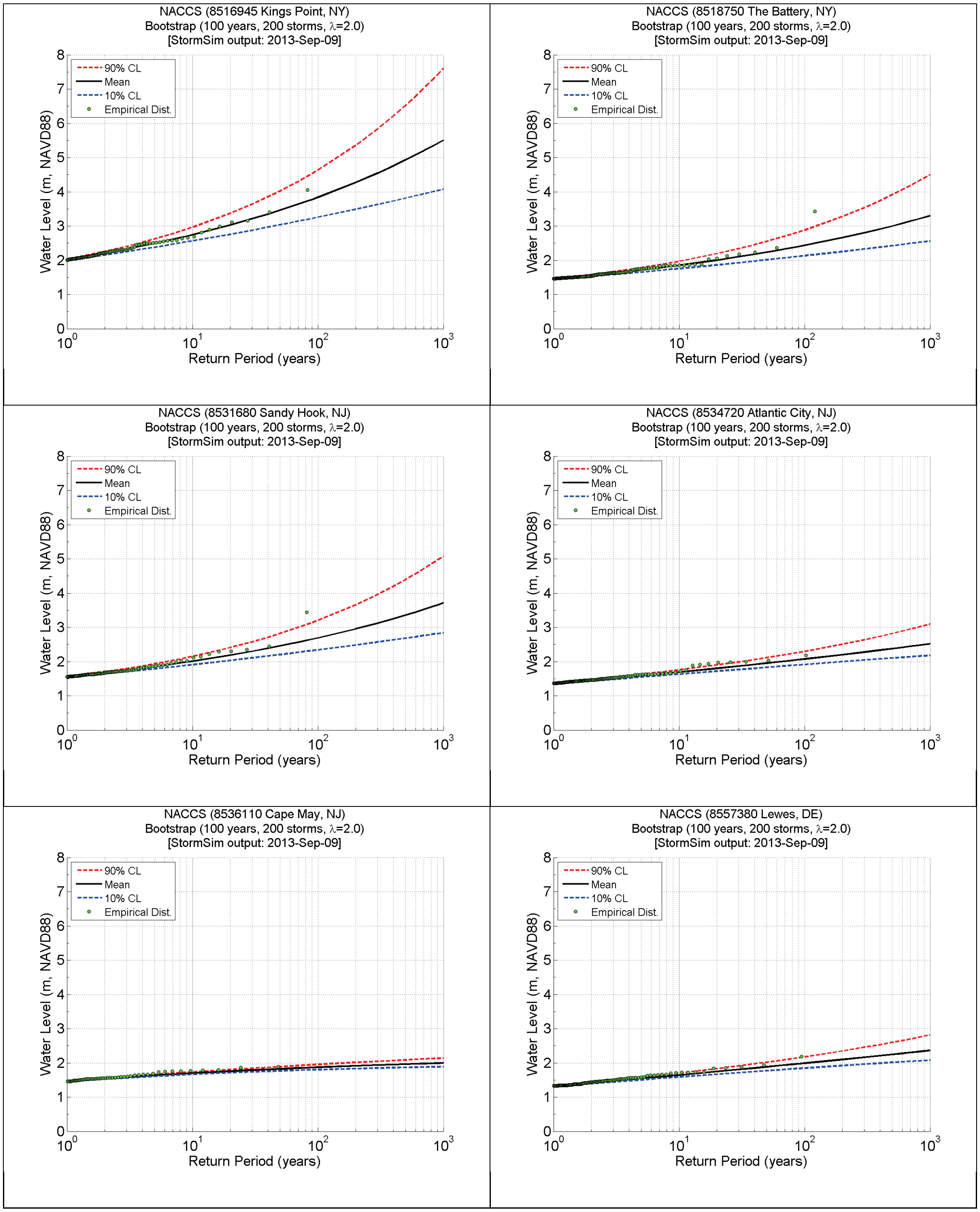

NACCS (8449130 Nantucket Island, MA)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
90% CL
Mean
10% CL
Empirical Dist.
Water Level (m, NAVD88)
Return Period (years)

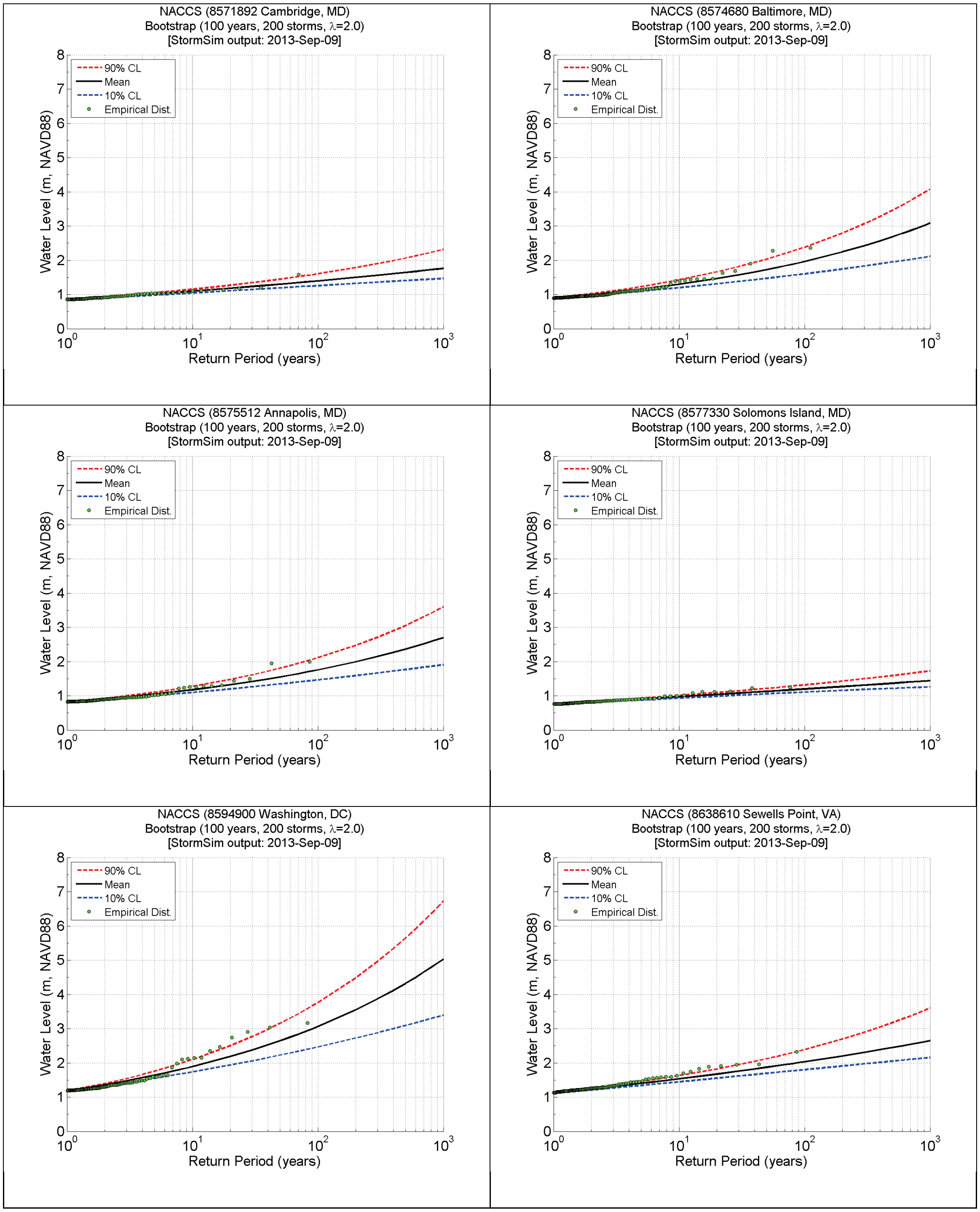

NACCS (8452660 Newport, RI)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
90% CL
Mean
10% CL
Empirical Dist.
Water Level (m, NAVD88)
Return Period (years)

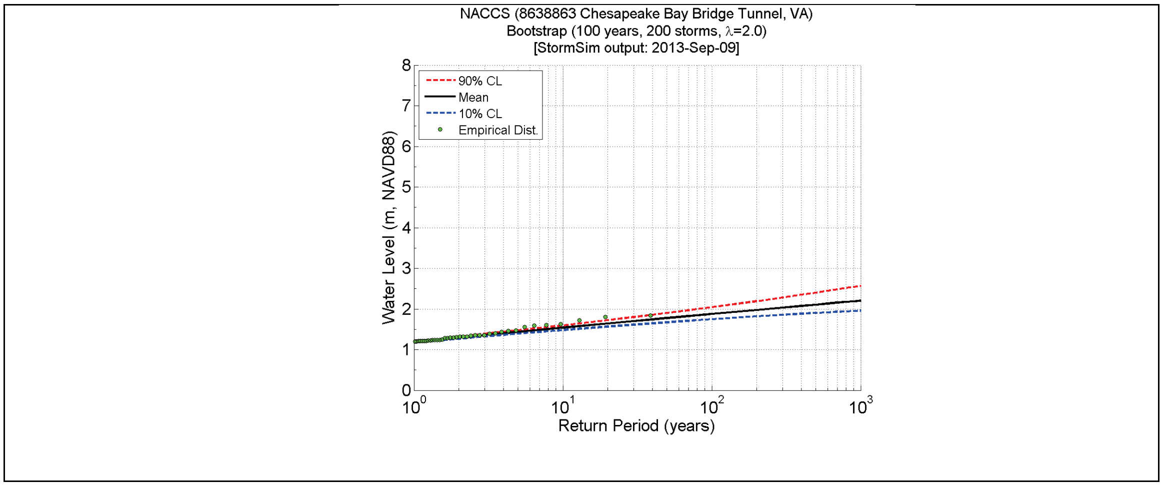

NACCS (8454000 Providence, RI)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
90% CL
Mean
10% CL
Empirical Dist.
Water Level (m, NAVD88)
Return Period (years)


NACCS (8461490 New London, CT)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
90% CL
Mean
10% CL
Empirical Dist.
Water Level (m, NAVD88)
Return Period (years)


NACCS (8510560 Montauk Point Light, NY)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
90% CL
Mean
10% CL
Empirical Dist.
Water Level (m, NAVD88)
Return Period (years)


NACCS (8516945 Kings Point, NY)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
NACCS (8518750 The Battery, NY)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
NACCS (8531680 Sandy Hook, NJ)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
NACCS (8534720 Atlantic City, NJ)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
NACCS (8536110 Cape May, NJ)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
NACCS (8557380 Lewes, DE)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
90% CL
Mean
10% CL
Empirical Dist.
Water Level (m, NAVD88)
Return Period (years)
0
1
2
3
4
5
6
7
8
10^0
10^1
10^2
10^3

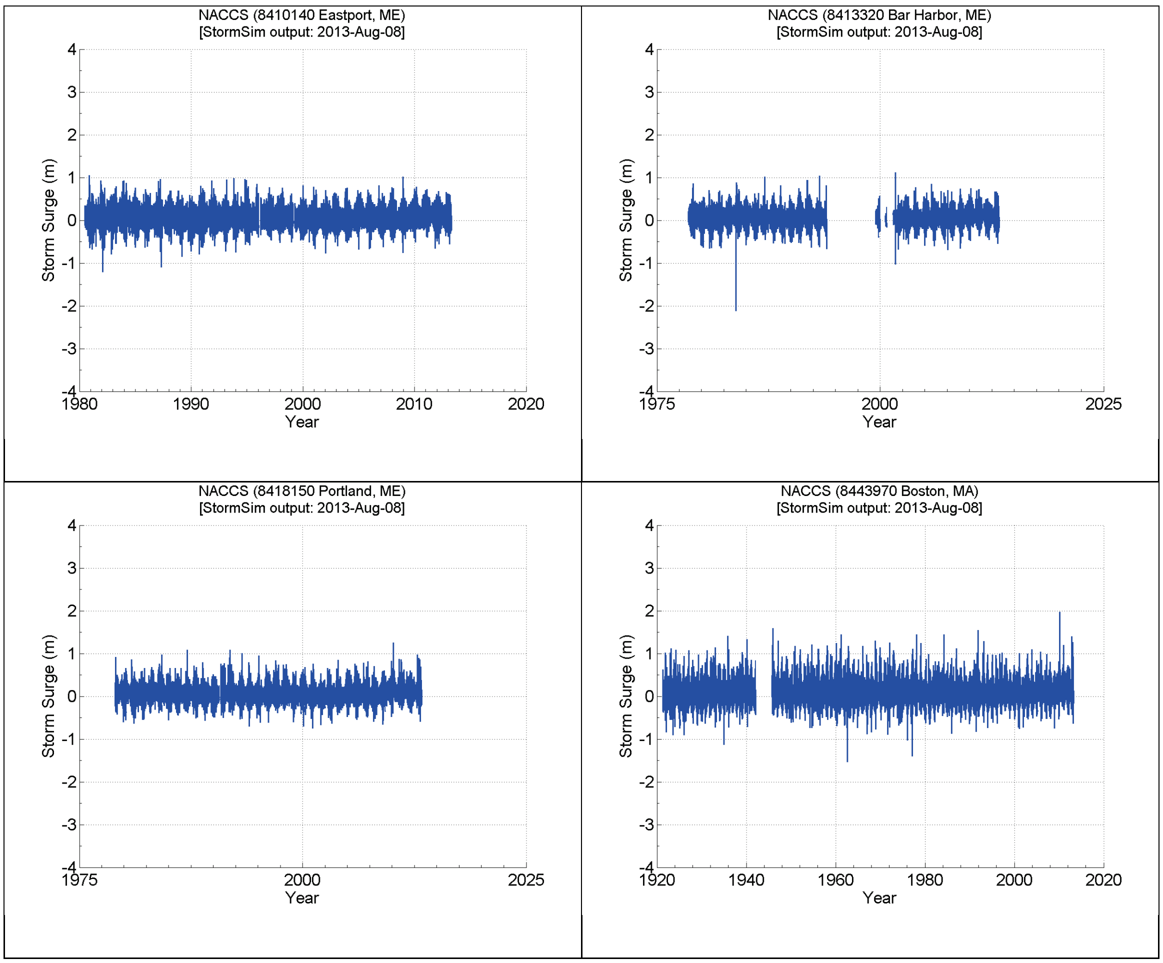

NACCS (8571892 Cambridge, MD)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
NACCS (8574680 Baltimore, MD)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
NACCS (8575512 Annapolis, MD)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
NACCS (8577330 Solomons Island, MD)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
NACCS (8594900 Washington, DC)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
NACCS (8638610 Sewells Point, VA)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
90% CL
Mean
10% CL
Empirical Dist.
Water Level (m, NAVD88)
Return Period (years)

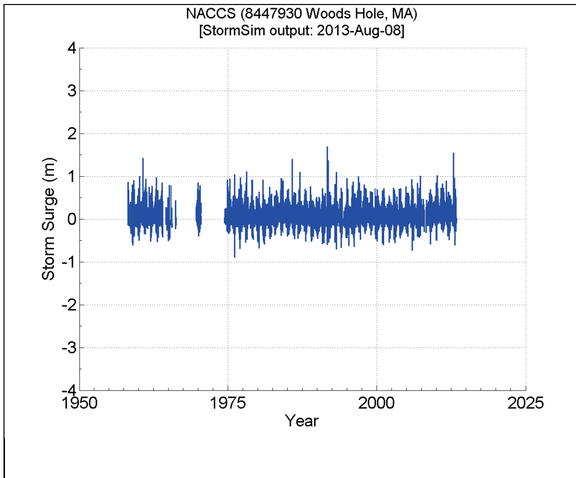

NACCS (8638863 Chesapeake Bay Bridge Tunnel, VA)
Bootstrap (100 years, 200 storms, λ=2.0)
[StormSim output: 2013-Sep-09]
90% CL
Mean
10% CL
Empirical Dist.
Water Level (m, NAVD88)
Return Period (years)

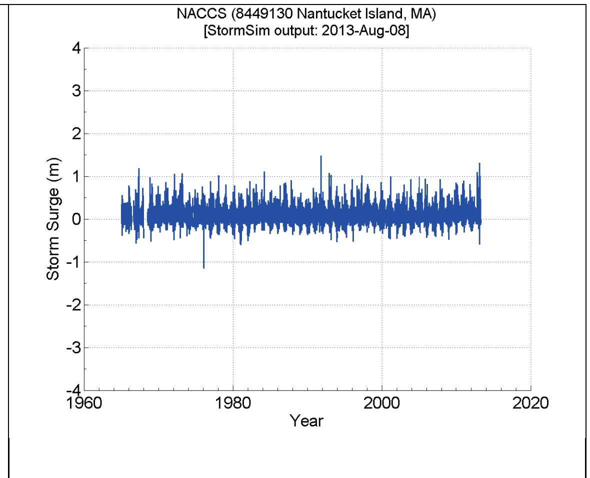
Appendix C: Monte Carlo Life-Cycle

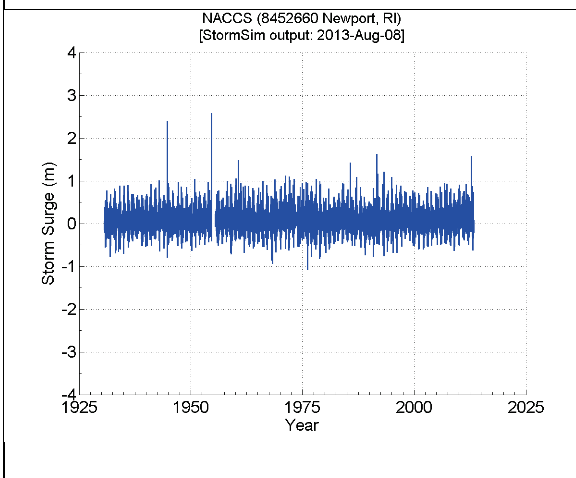
Storm surge time histories

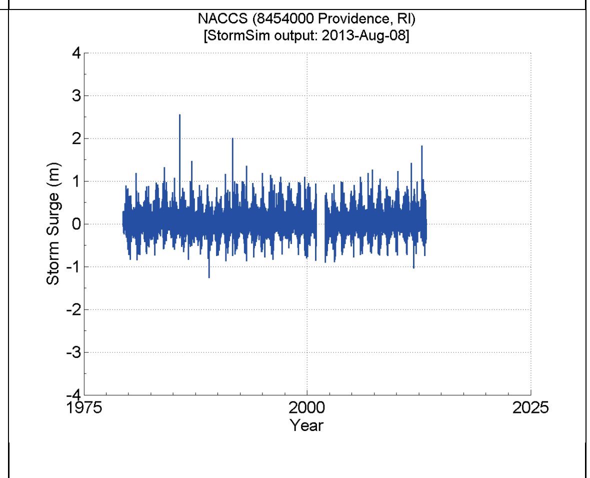
The following pages present time series of hourly water level residuals from measurements for the 23 gages listed in Table 1.

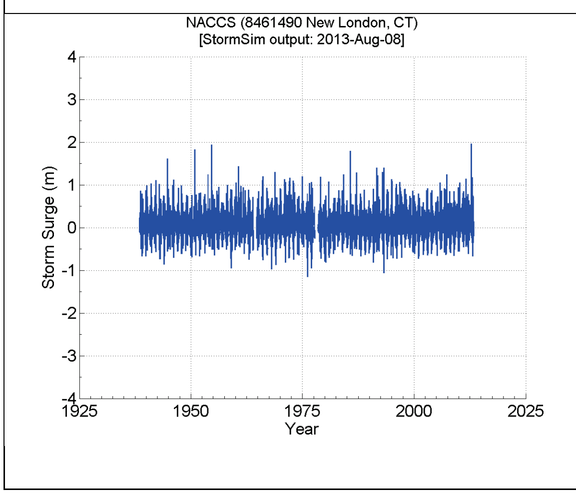


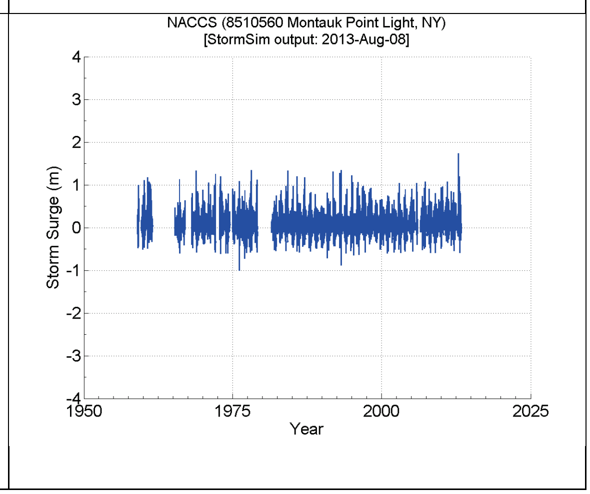

NACCS (8447930 Woods Hole, MA)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Year
4
3
2
1
0
-1
-2
-3
-4
1950
1975
2000
2025

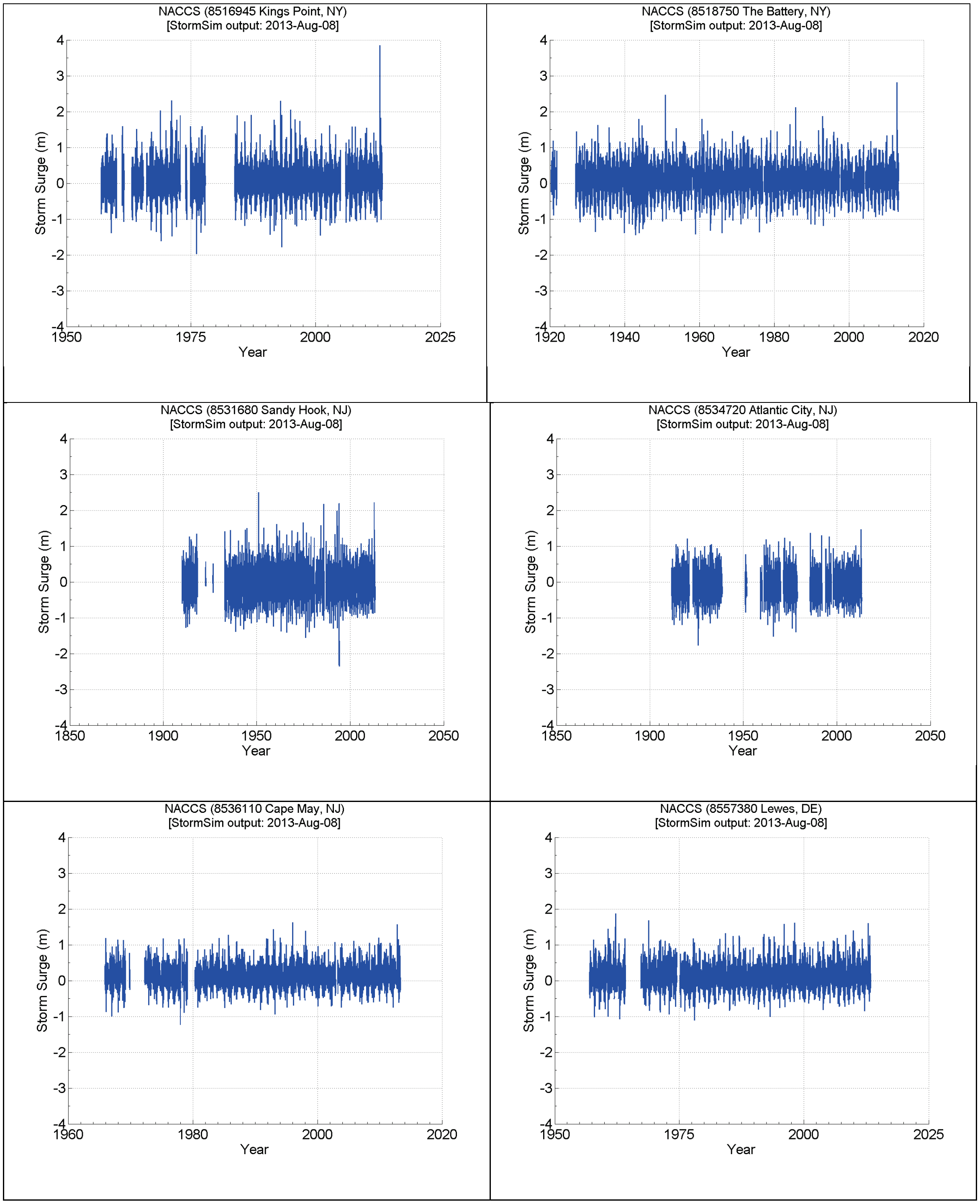

NACCS (8449130 Nantucket Island, MA)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Year
4
3
2
1
0
-1
-2
-3
-4
1960
1980
2000
2020

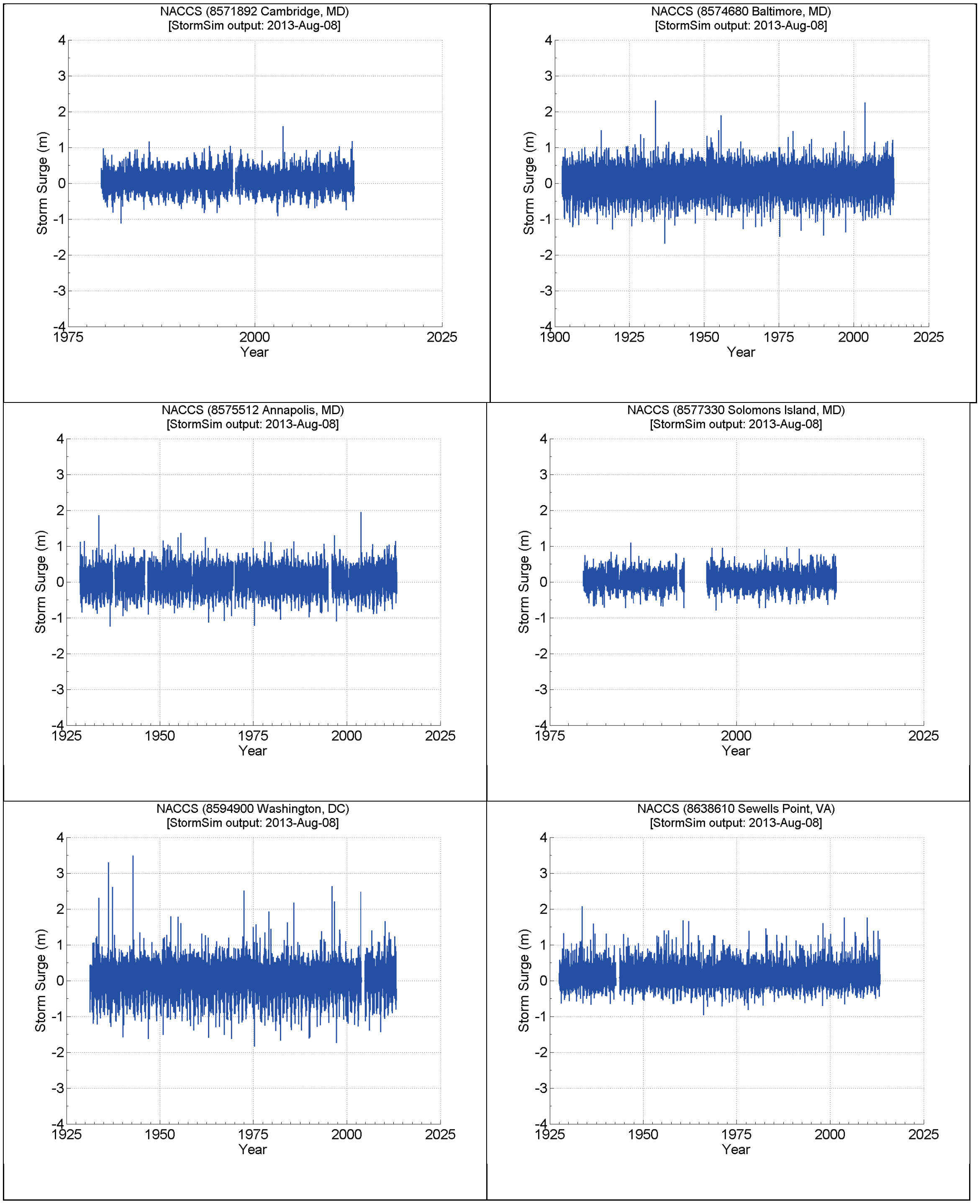

NACCS (8452660 Newport, RI)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Year
4
3
2
1
0
-1
-2
-3
-4
1925
1950
1975
2000
2025

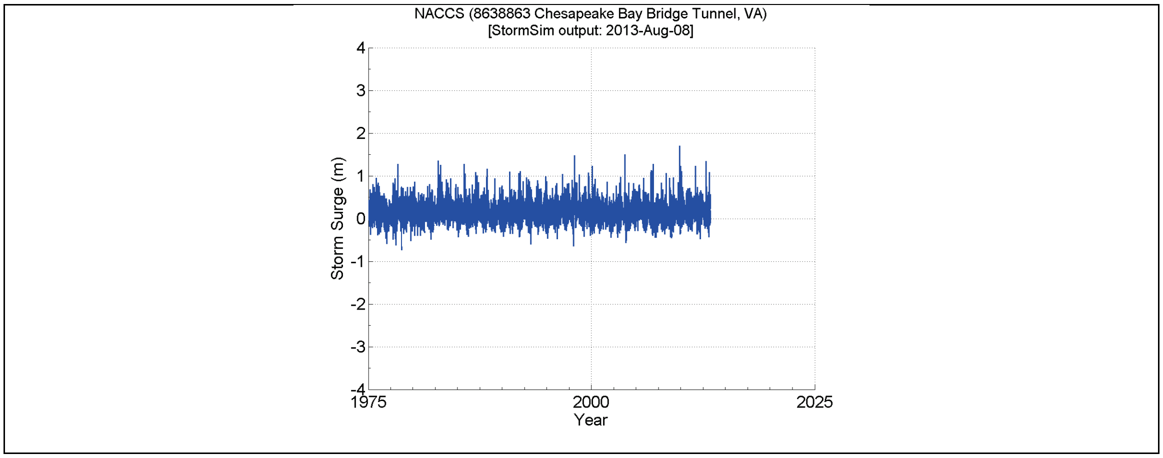

NACCS (8454000 Providence, RI)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Year
4
3
2
1
0
-1
-2
-3
-4
1975
2000
2025


NACCS (8461490 New London, CT)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Year
4
3
2
1
0
-1
-2
-3
-4
1925
1950
1975
2000
2025


NACCS (8510560 Montauk Point Light, NY)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Year
4
3
2
1
0
-1
-2
-3
-4
1950
1975
2000
2025

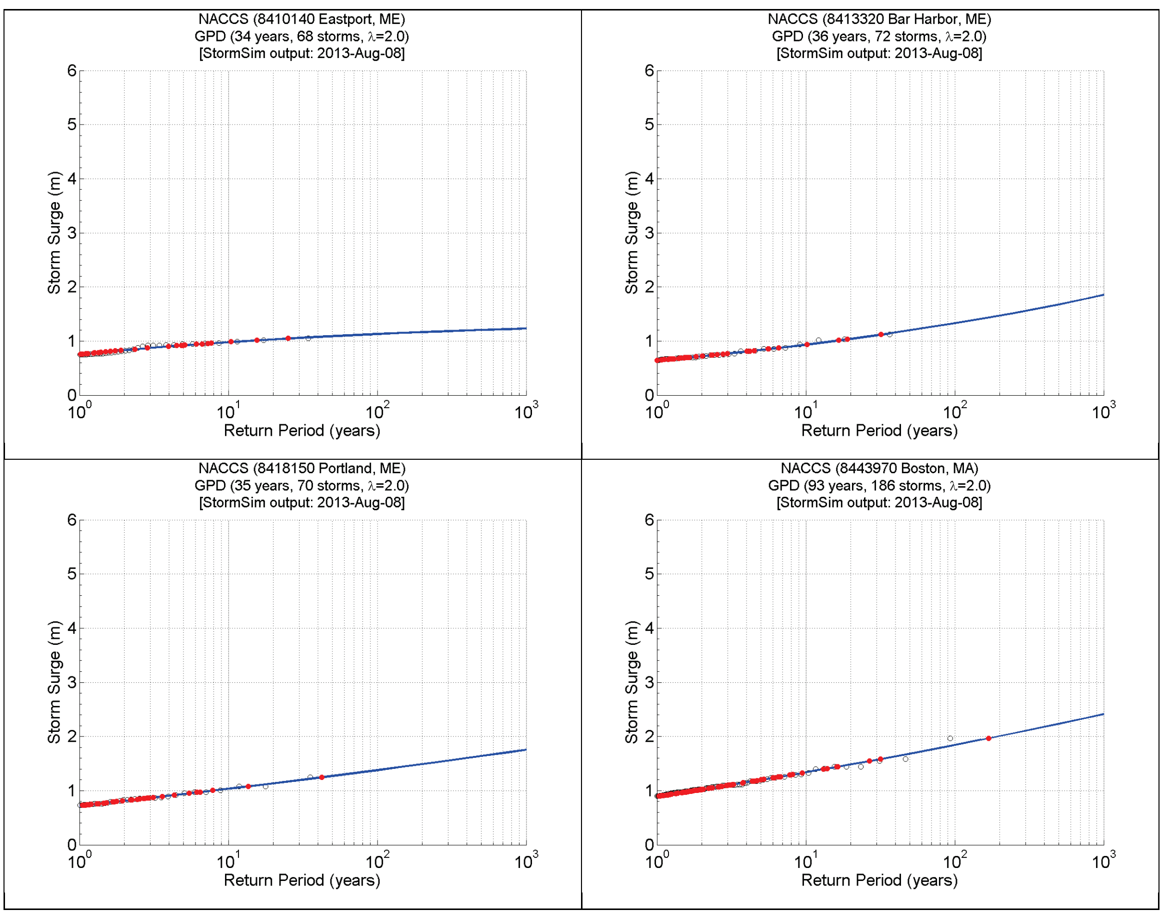

NACCS (8516945 Kings Point, NY)
[StormSim output: 2013-Aug-08]
NACCS (8518750 The Battery, NY)
[StormSim output: 2013-Aug-08]
NACCS (8531680 Sandy Hook, NJ)
[StormSim output: 2013-Aug-08]
NACCS (8534720 Atlantic City, NJ)
[StormSim output: 2013-Aug-08]
NACCS (8536110 Cape May, NJ)
[StormSim output: 2013-Aug-08]
NACCS (8557380 Lewes, DE)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Year

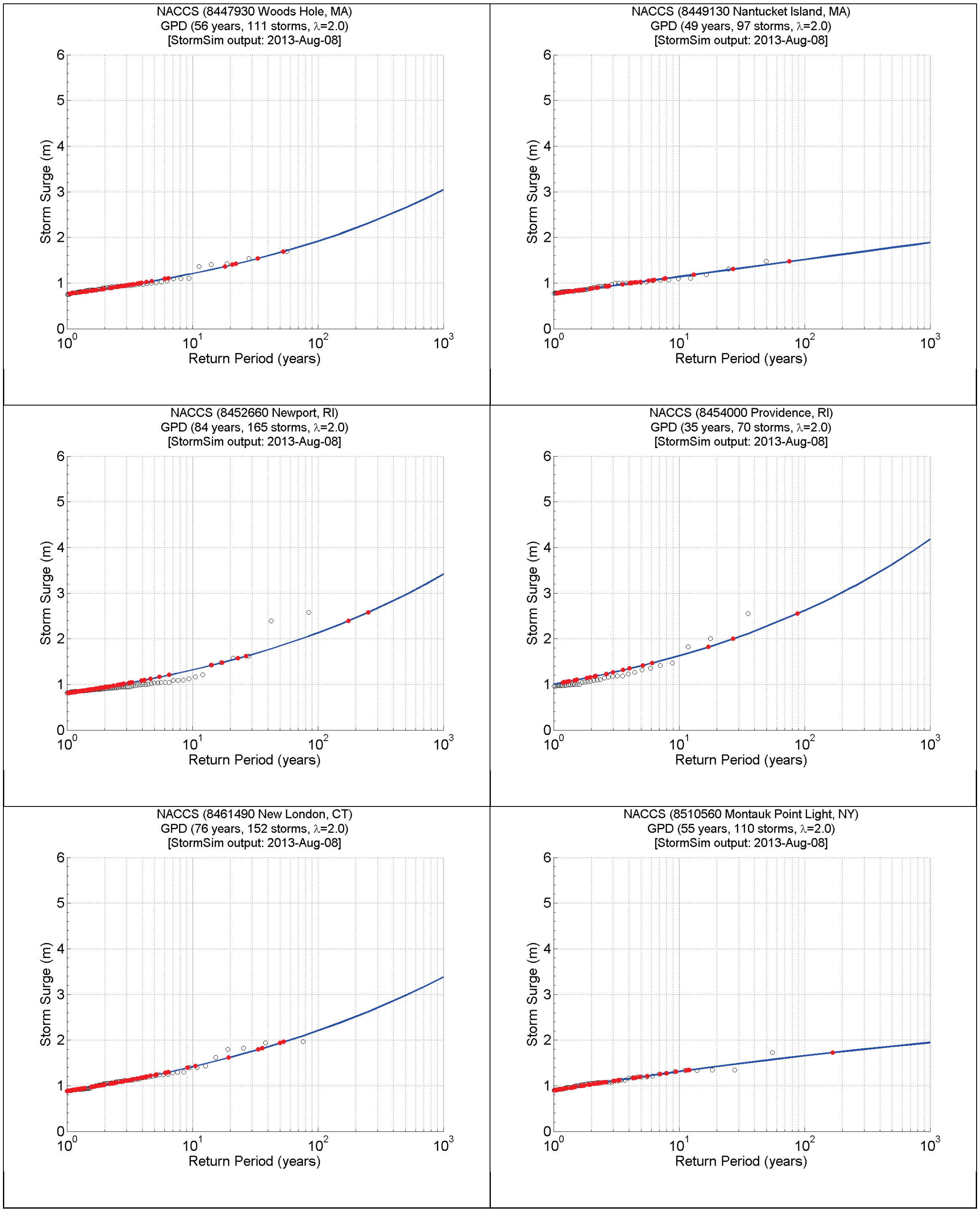

NACCS (8571892 Cambridge, MD)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Year
NACCS (8574680 Baltimore, MD)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Year
NACCS (8575512 Annapolis, MD)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Year
NACCS (8577330 Solomons Island, MD)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Year
NACCS (8594900 Washington, DC)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Year
NACCS (8638610 Sewells Point, VA)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Year

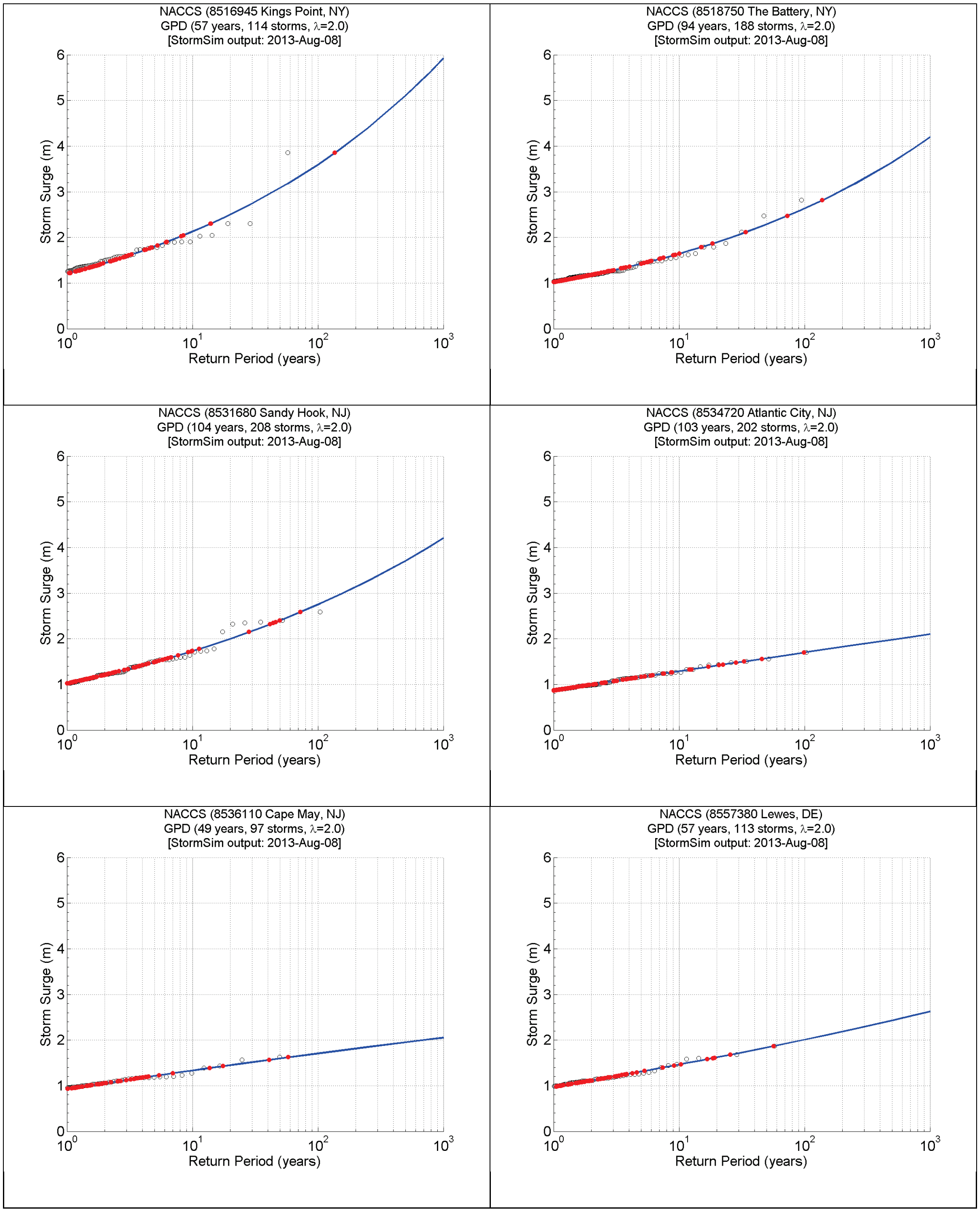


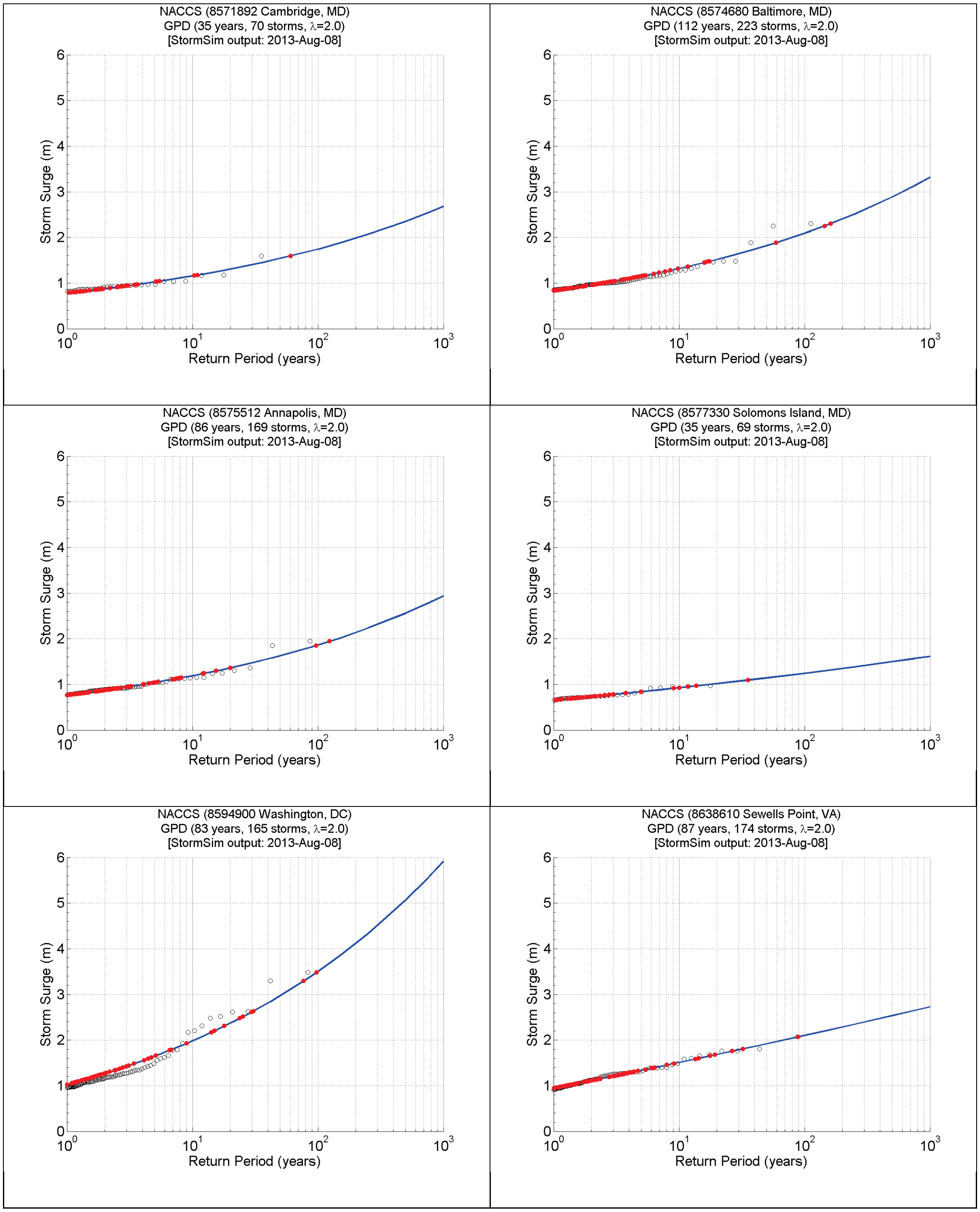
Extremal analysis of storm surge

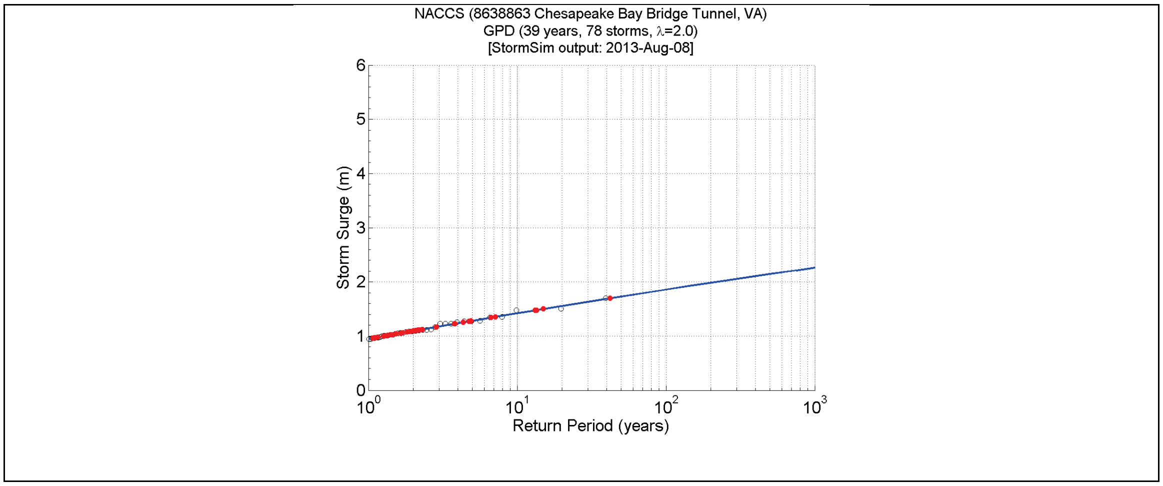
The following figures provide the results of the extremal analysis of storm surge for the 23 gages. Storm surge as a function of return period are plotted for the empirical cumulative distribution function (open circles), GPD parametric fit (blue solid line), and the empirical values adjusted based on the parametric fit (red solid circles).




NACCS (8447930 Woods Hole, MA)
GPD (56 years, 111 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
NACCS (8449130 Nantucket Island, MA)
GPD (49 years, 97 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
NACCS (8452660 Newport, RI)
GPD (84 years, 165 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
NACCS (8454000 Providence, RI)
GPD (35 years, 70 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
NACCS (8461490 New London, CT)
GPD (76 years, 152 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
NACCS (8510560 Montauk Point Light, NY)
GPD (55 years, 110 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Return Period (years)

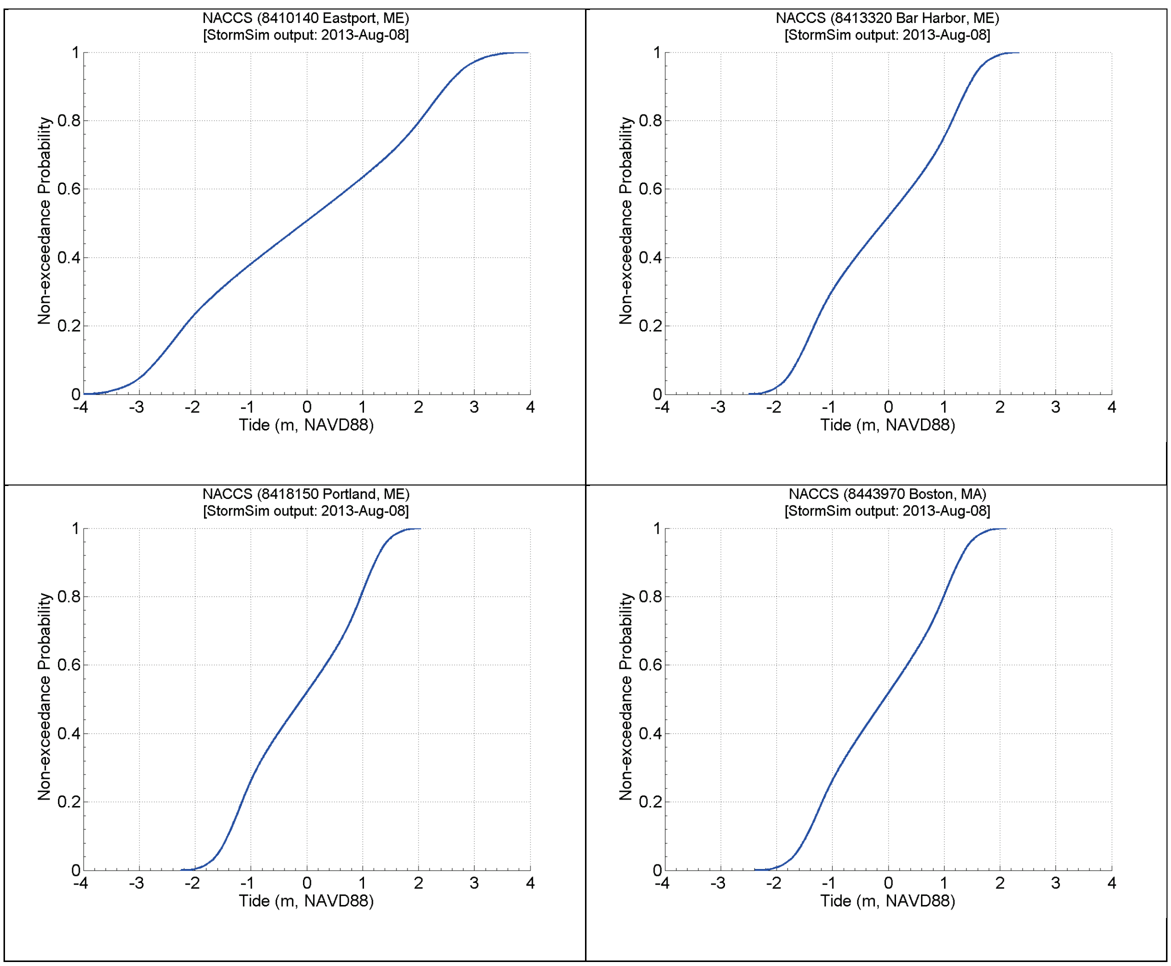

NACCS (8516945 Kings Point, NY)
GPD (57 years, 114 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
NACCS (8518750 The Battery, NY)
GPD (94 years, 188 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
NACCS (8531680 Sandy Hook, NJ)
GPD (104 years, 208 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
NACCS (8534720 Atlantic City, NJ)
GPD (103 years, 202 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
NACCS (8536110 Cape May, NJ)
GPD (49 years, 97 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
NACCS (8557380 Lewes, DE)
GPD (57 years, 113 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Return Period (years)

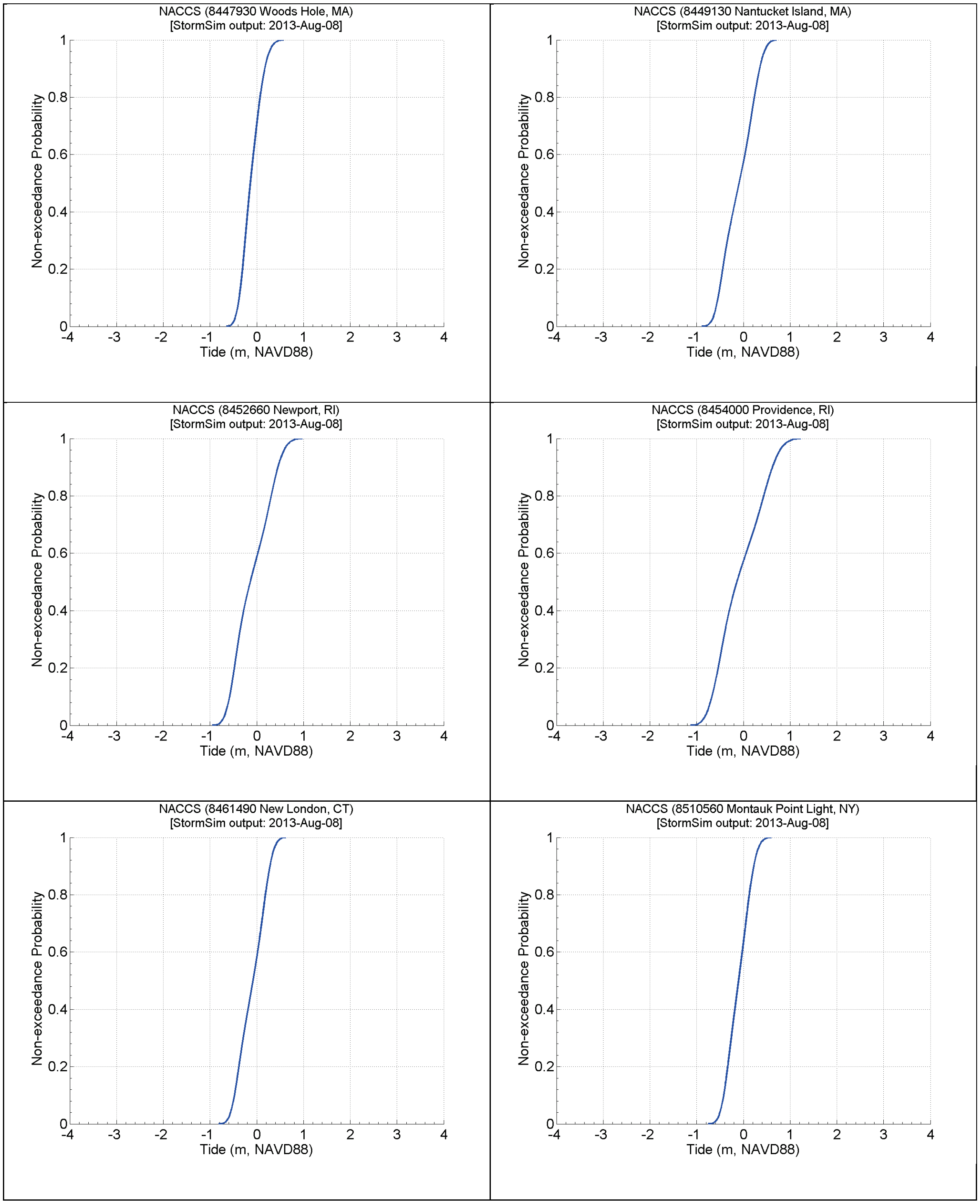

NACCS (8571892 Cambridge, MD)
GPD (35 years, 70 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Return Period (years)
NACCS (8574680 Baltimore, MD)
GPD (112 years, 223 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Return Period (years)
NACCS (8575512 Annapolis, MD)
GPD (86 years, 169 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Return Period (years)
NACCS (8577330 Solomons Island, MD)
GPD (35 years, 69 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Return Period (years)
NACCS (8594900 Washington, DC)
GPD (83 years, 165 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Return Period (years)
NACCS (8638610 Sewells Point, VA)
GPD (87 years, 174 storms, λ=2.0)
[StormSim output: 2013-Aug-08]
Storm Surge (m)
Return Period (years)

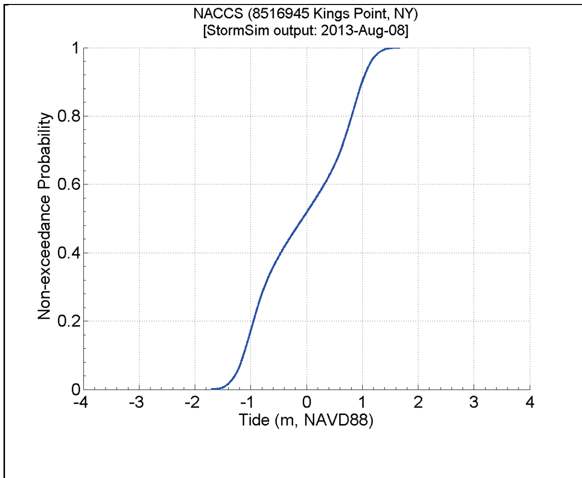


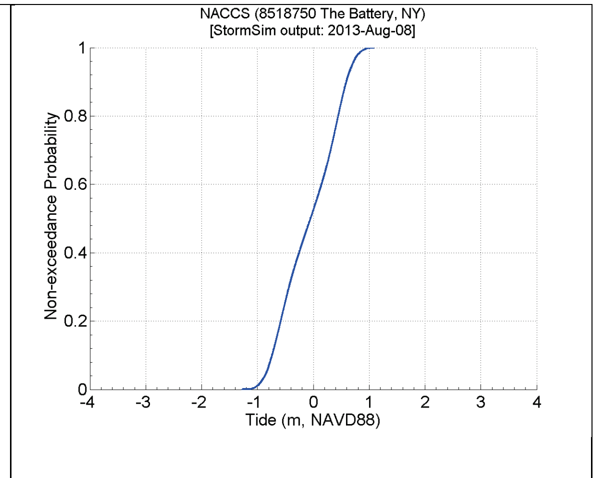
Astronomical tide empirical cumulative distribution function

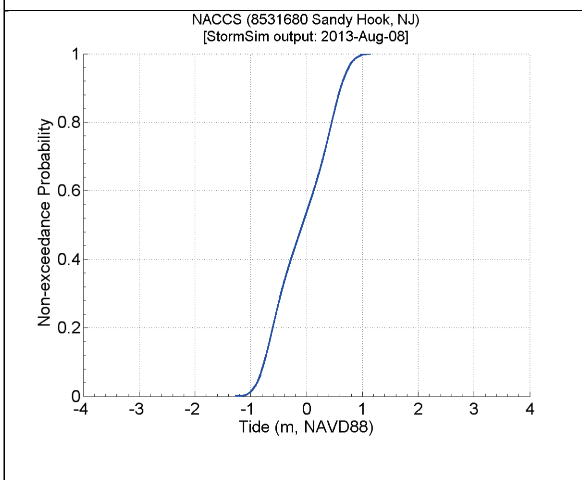
The following pages present the empirical CDF of astronomical tide for the 23 gages listed in Table 1.

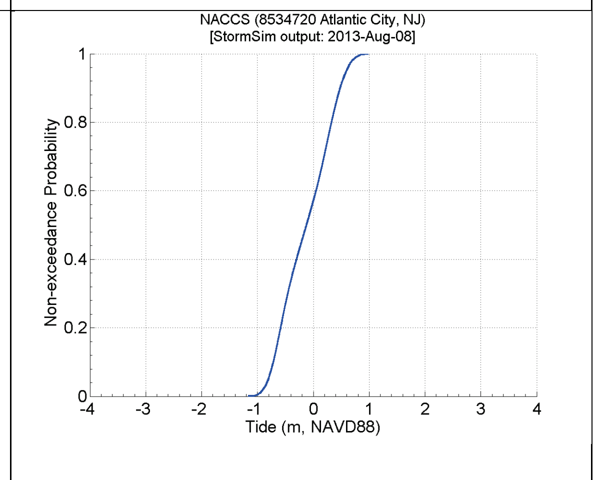


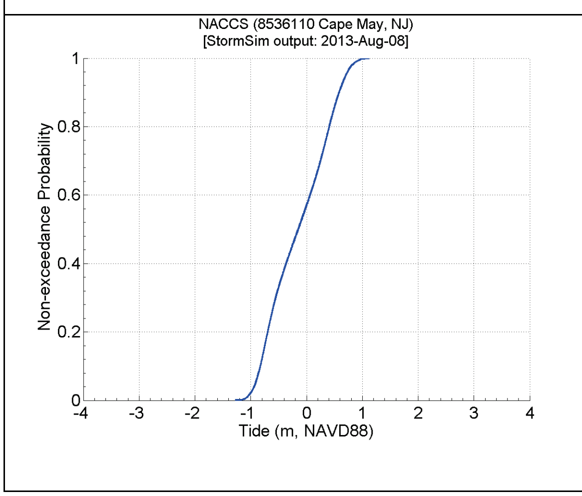

NACCS (8447930 Woods Hole, MA)
[StormSim output: 2013-Aug-08]
NACCS (8449130 Nantucket Island, MA)
[StormSim output: 2013-Aug-08]
NACCS (8452660 Newport, RI)
[StormSim output: 2013-Aug-08]
NACCS (8454000 Providence, RI)
[StormSim output: 2013-Aug-08]
NACCS (8461490 New London, CT)
[StormSim output: 2013-Aug-08]
NACCS (8510560 Montauk Point Light, NY)
[StormSim output: 2013-Aug-08]
Non-exceedance Probability
Tide (m, NAVD88)

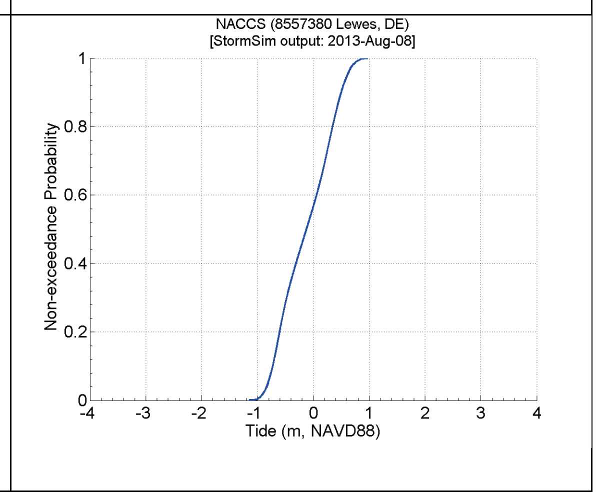

NACCS (8516945 Kings Point, NY)
[StormSim output: 2013-Aug-08]
Non-exceedance Probability
Tide (m, NAVD88)

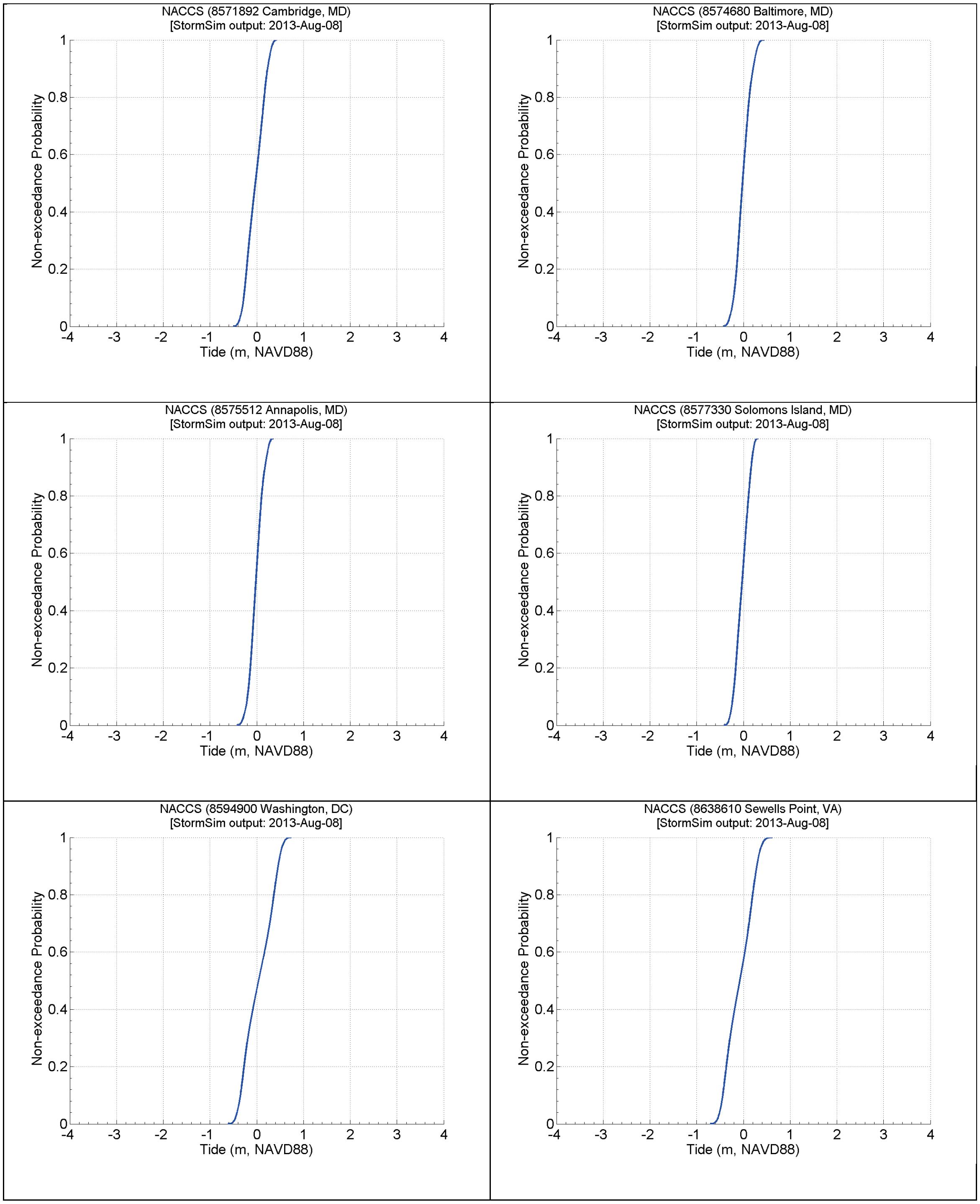

NACCS (8518750 The Battery, NY)
[StormSim output: 2013-Aug-08]
Non-exceedance Probability
Tide (m, NAVD88)

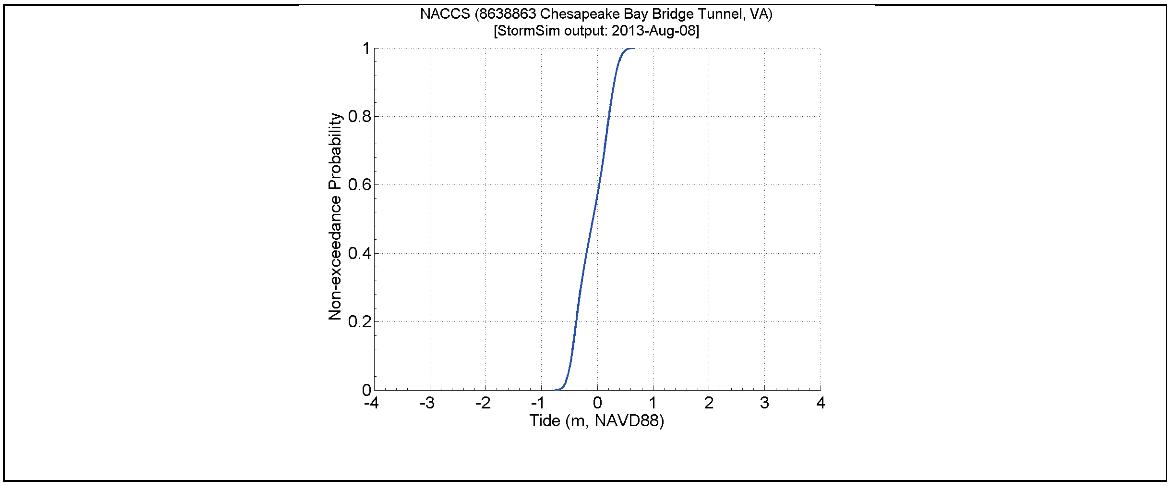

NACCS (8531680 Sandy Hook, NJ)
[StormSim output: 2013-Aug-08]
Non-exceedance Probability
Tide (m, NAVD88)


NACCS (8534720 Atlantic City, NJ)
[StormSim output: 2013-Aug-08]
Non-exceedance Probability
Tide (m, NAVD88)


NACCS (8536110 Cape May, NJ)
[StormSim output: 2013-Aug-08]
Non-exceedance Probability
Tide (m, NAVD88)

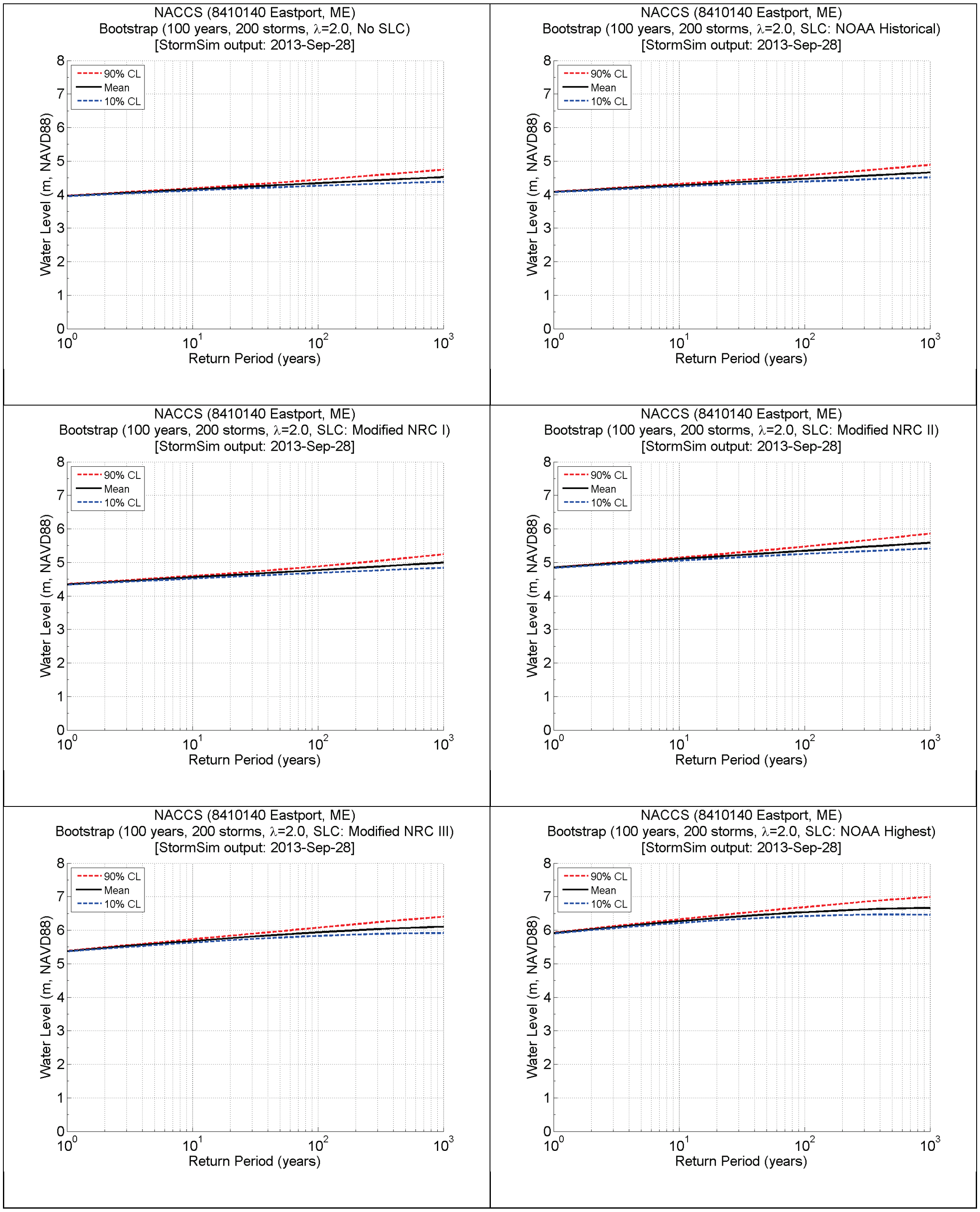

NACCS (8557380 Lewes, DE)
[StormSim output: 2013-Aug-08]
Non-exceedance Probability
Tide (m, NAVD88)

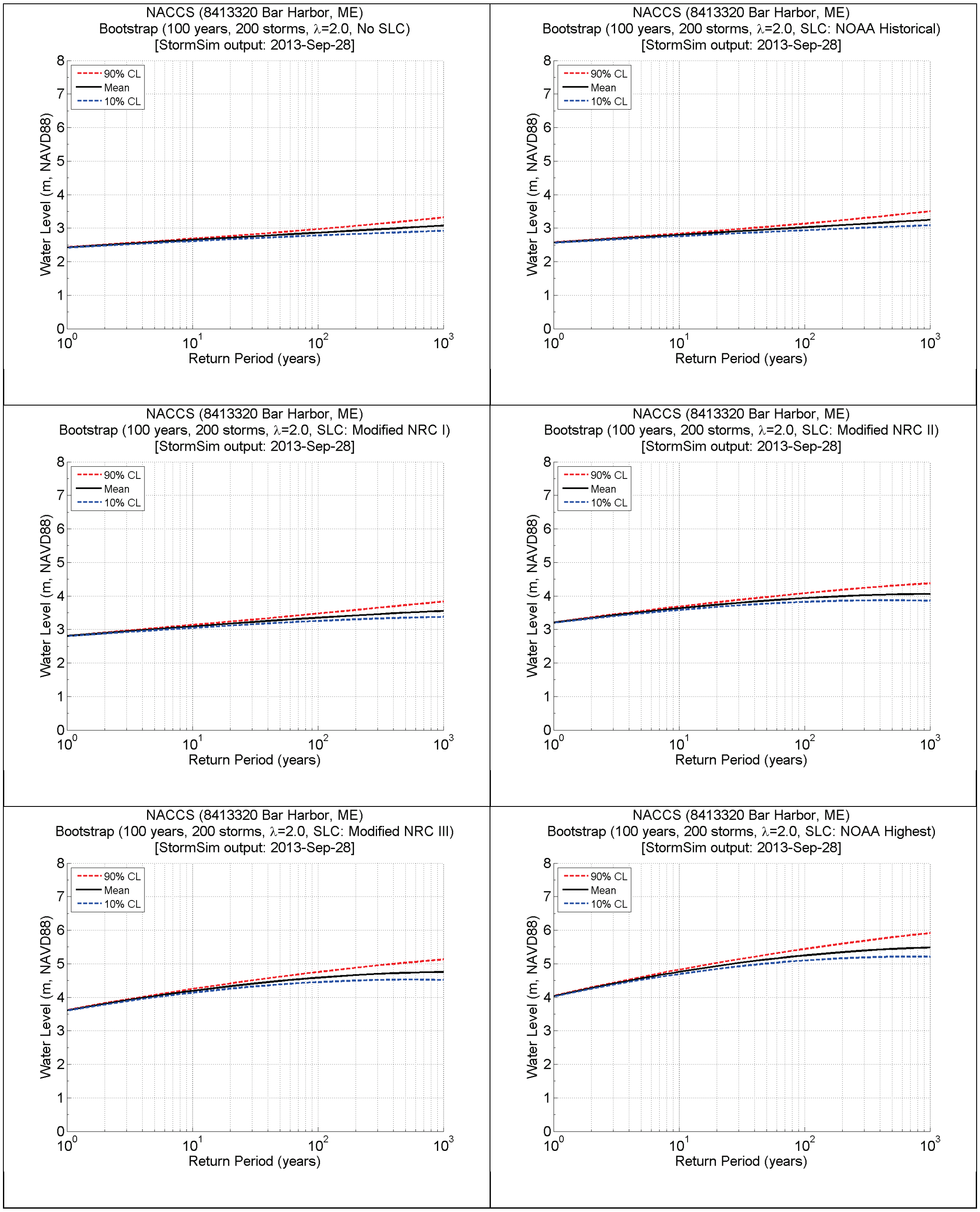

NACCS (8571892 Cambridge, MD)
[StormSim output: 2013-Aug-08]
NACCS (8574680 Baltimore, MD)
[StormSim output: 2013-Aug-08]
NACCS (8575512 Annapolis, MD)
[StormSim output: 2013-Aug-08]
NACCS (8577330 Solomons Island, MD)
[StormSim output: 2013-Aug-08]
NACCS (8594900 Washington, DC)
[StormSim output: 2013-Aug-08]
NACCS (8638610 Sewells Point, VA)
[StormSim output: 2013-Aug-08]
Non-exceedance Probability
Tide (m, NAVD88)
0
0.2
0.4
0.6
0.8
1
-4
-3
-2
-1
0
1
2
3
4

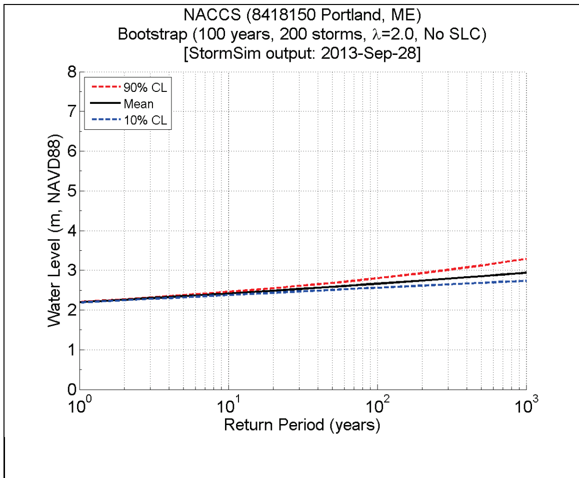

NACCS (8638863 Chesapeake Bay Bridge Tunnel, VA)
[StormSim output: 2013-Aug-08]
Non-exceedance Probability
Tide (m, NAVD88)
1
0.8
0.6
0.4
0.2
0
-4
-3
-2
-1
0
1
2
3
4

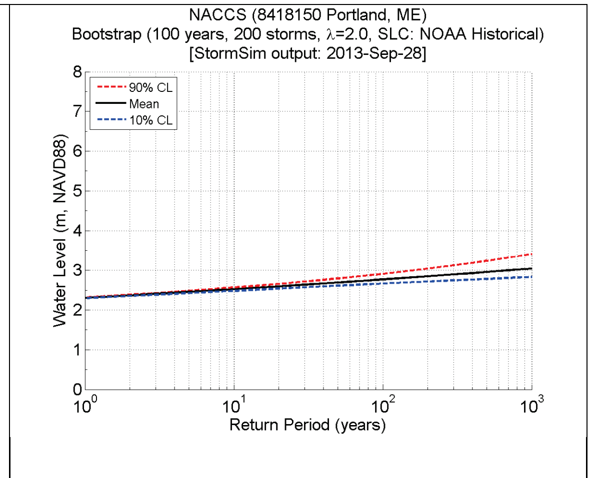
Appendix D: Future Extreme Water Levels

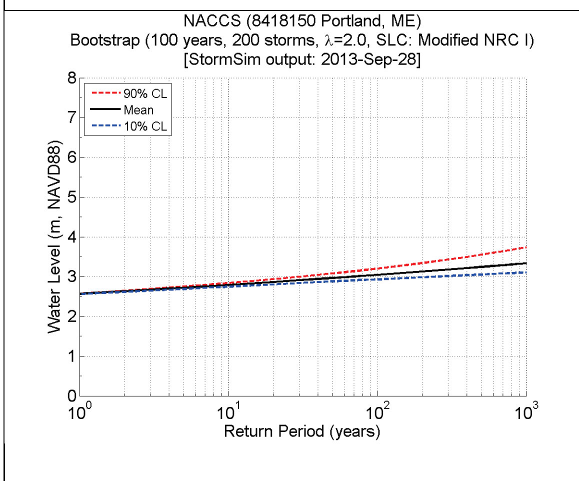
The following figures provide the results of the MCLC extremal analysis of storm water levels for the 23 gages, for all SLC scenarios. Water levels as a function of return period are plotted for the mean continuous distribution and 10% and 90% CL.

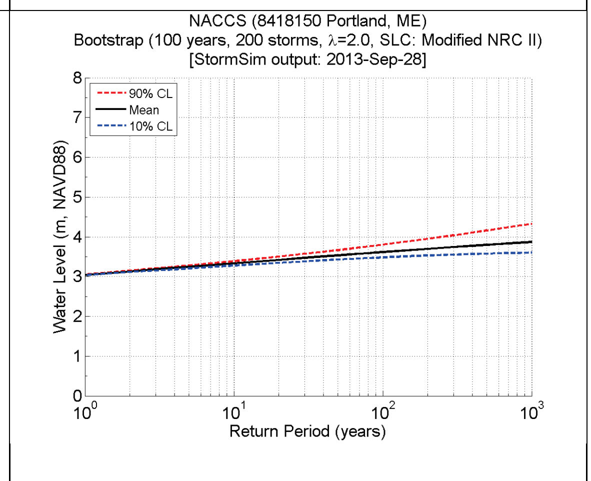

NACCS (8410140 Eastport, ME)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
NACCS (8410140 Eastport, ME)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
NACCS (8410140 Eastport, ME)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
NACCS (8410140 Eastport, ME)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
NACCS (8410140 Eastport, ME)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
NACCS (8410140 Eastport, ME)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
0
1
2
3
4
5
6
7
8
10^0
10^1
10^2
10^3

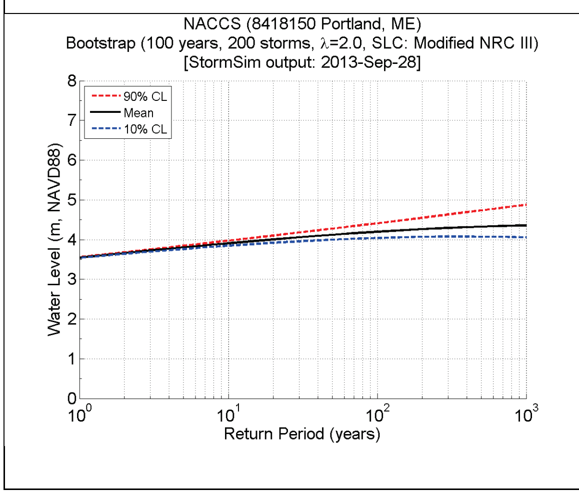

NACCS (8413320 Bar Harbor, ME)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
NACCS (8413320 Bar Harbor, ME)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
NACCS (8413320 Bar Harbor, ME)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
NACCS (8413320 Bar Harbor, ME)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
NACCS (8413320 Bar Harbor, ME)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
NACCS (8413320 Bar Harbor, ME)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

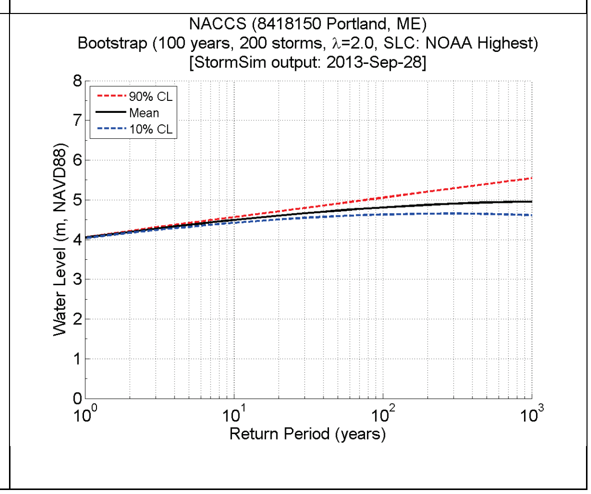

NACCS (8418150 Portland, ME)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

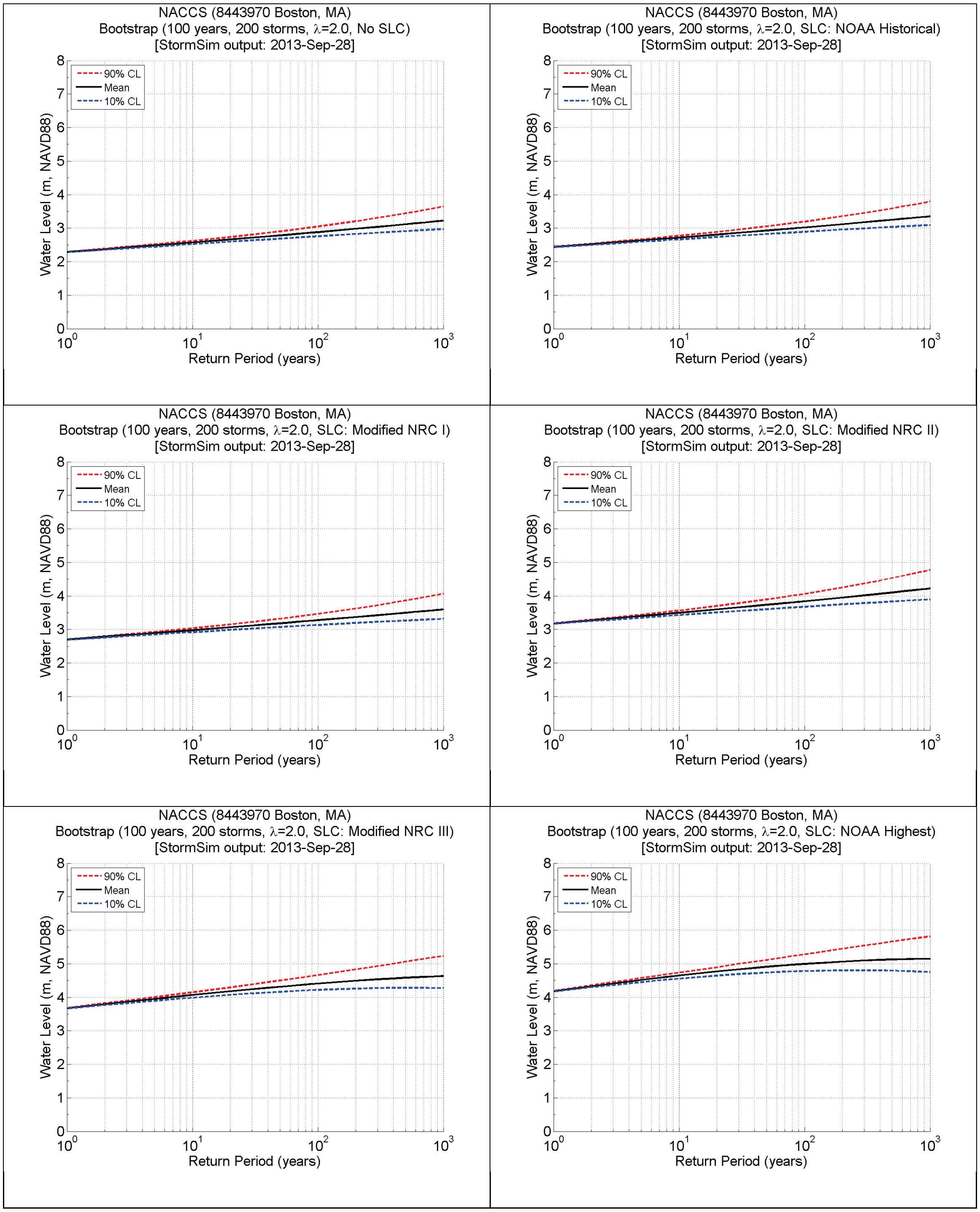

NACCS (8418150 Portland, ME)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

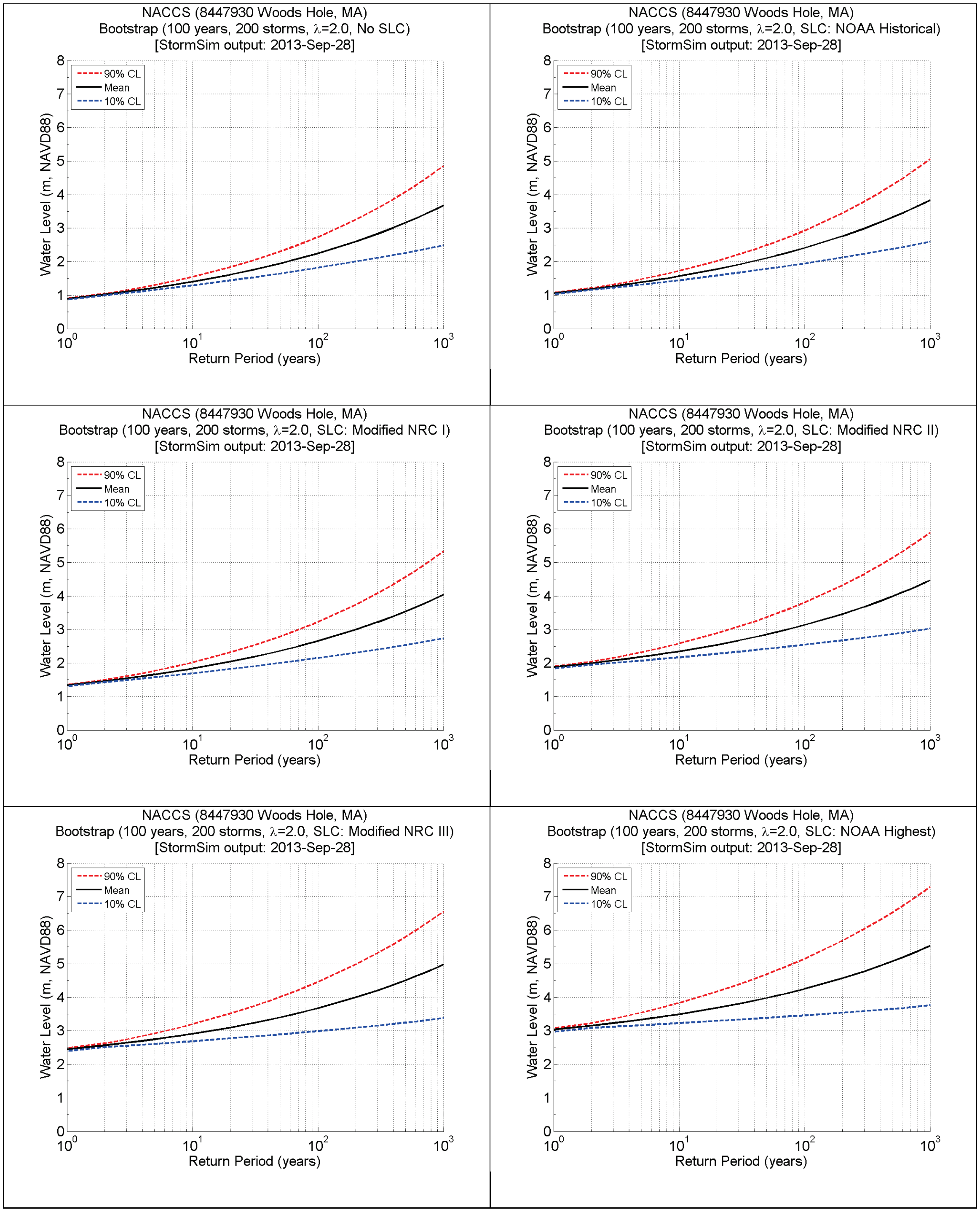

NACCS (8418150 Portland, ME)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

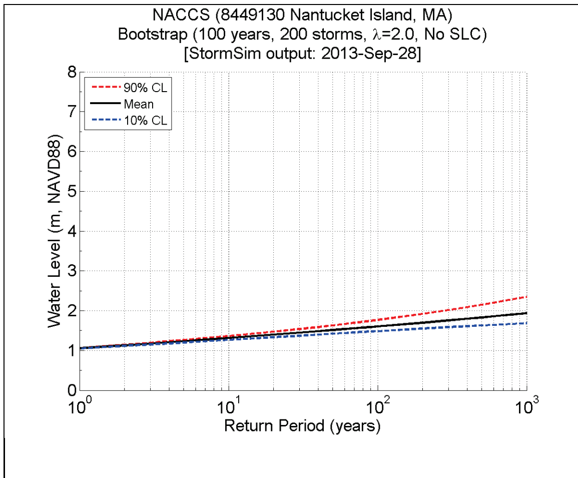

NACCS (8418150 Portland, ME)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

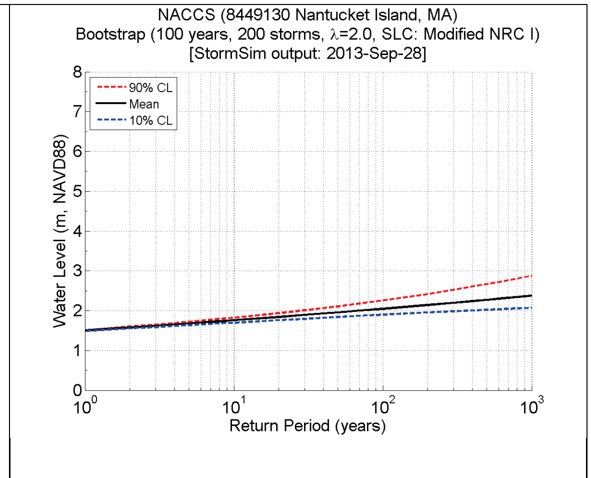

NACCS (8418150 Portland, ME)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

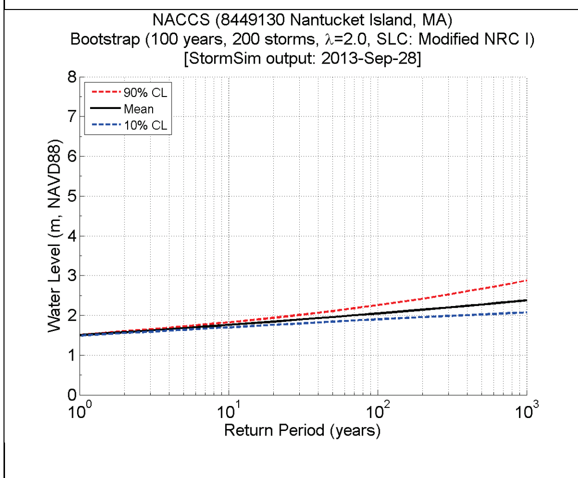

NACCS (8418150 Portland, ME)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

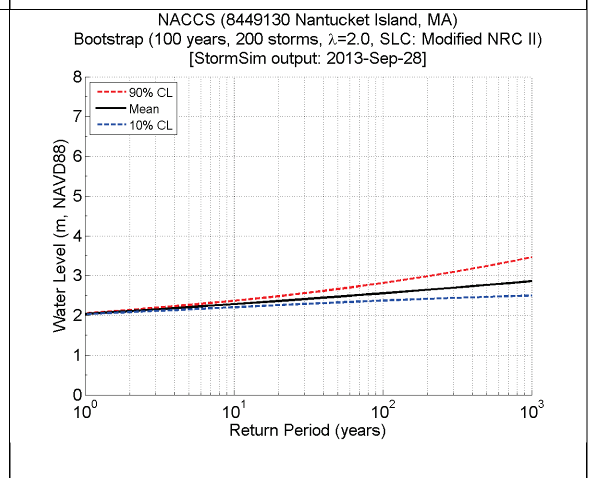

NACCS (8443970 Boston, MA)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8443970 Boston, MA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
NACCS (8443970 Boston, MA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
NACCS (8443970 Boston, MA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
NACCS (8443970 Boston, MA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
NACCS (8443970 Boston, MA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]

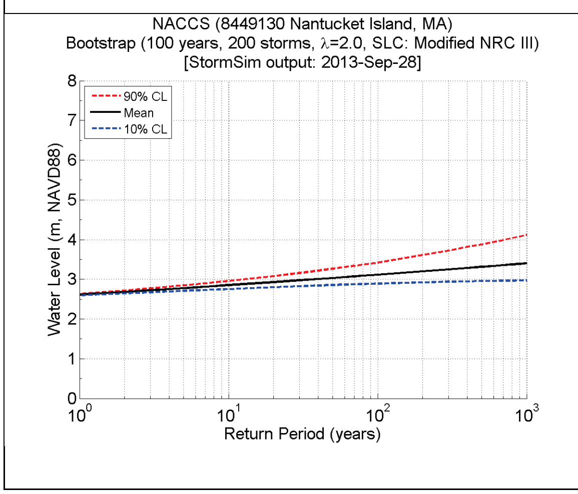

NACCS (8447930 Woods Hole, MA)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
NACCS (8447930 Woods Hole, MA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
NACCS (8447930 Woods Hole, MA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
NACCS (8447930 Woods Hole, MA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
NACCS (8447930 Woods Hole, MA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
NACCS (8447930 Woods Hole, MA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

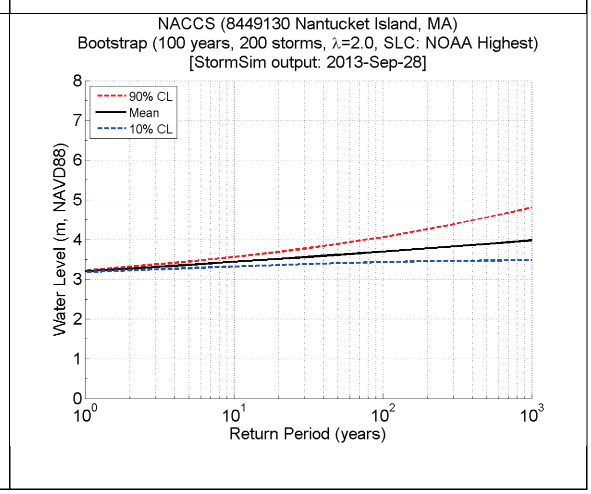

NACCS (8449130 Nantucket Island, MA)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

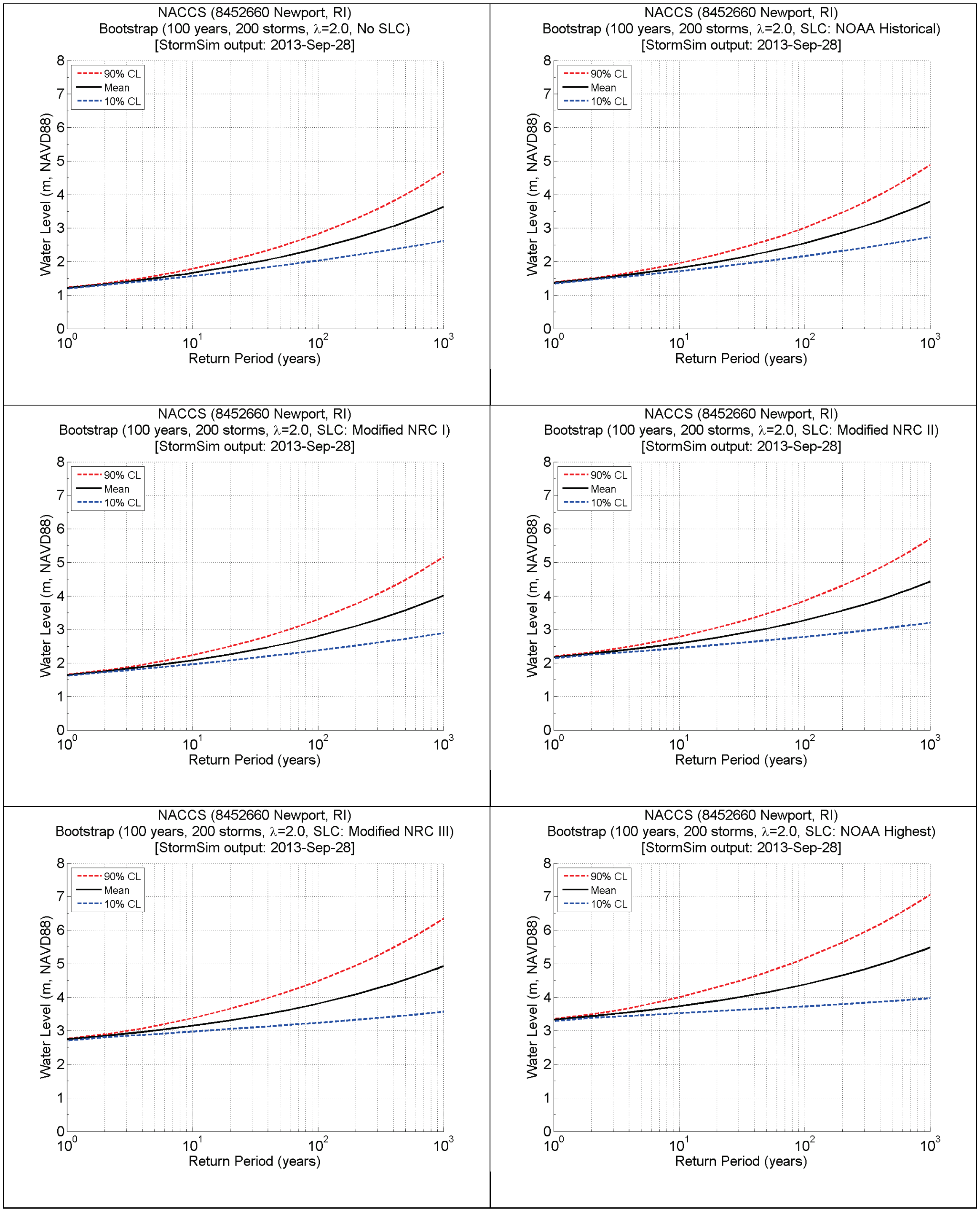

NACCS (8449130 Nantucket Island, MA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)


NACCS (8449130 Nantucket Island, MA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

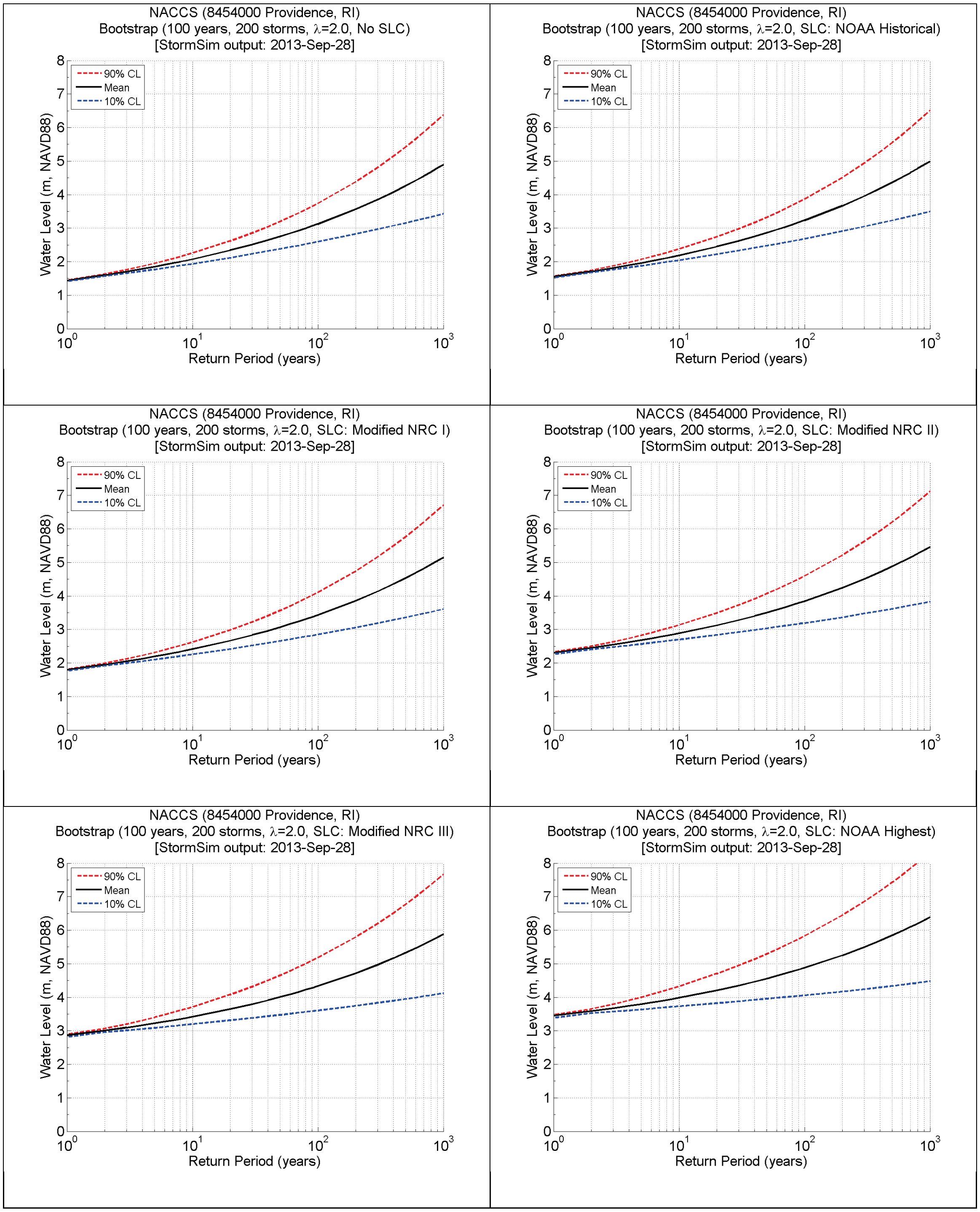

NACCS (8449130 Nantucket Island, MA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

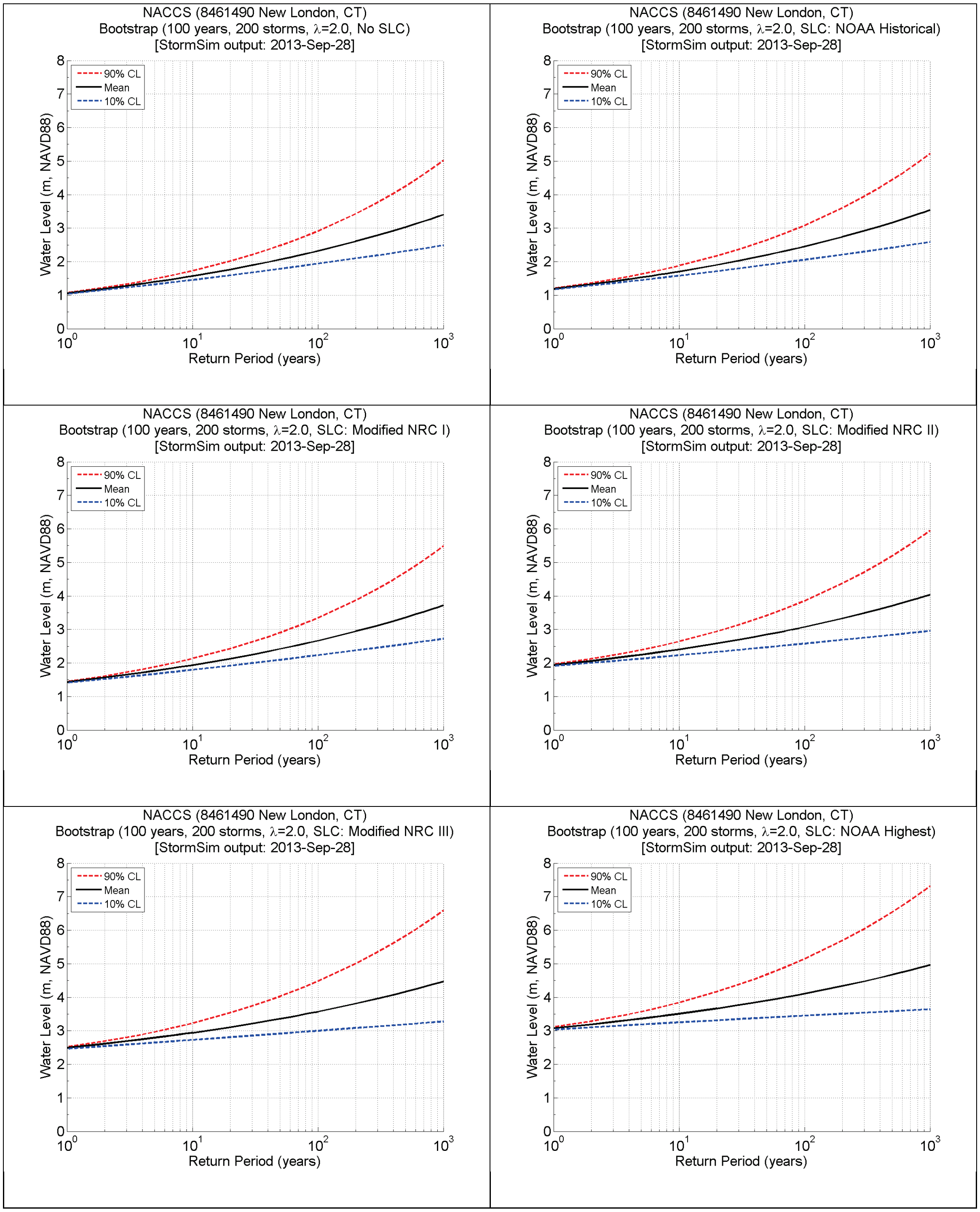

NACCS (8449130 Nantucket Island, MA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

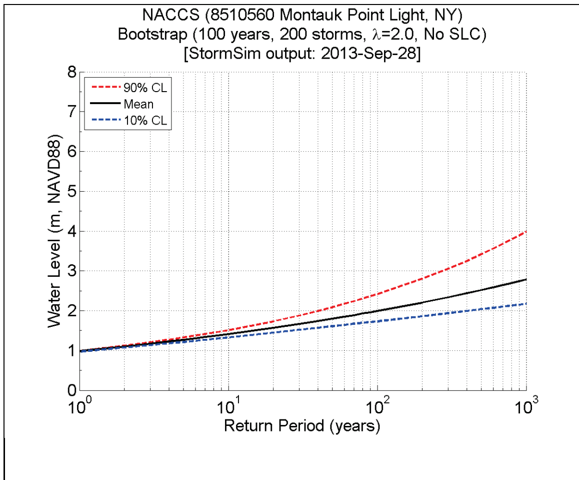

NACCS (8449130 Nantucket Island, MA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

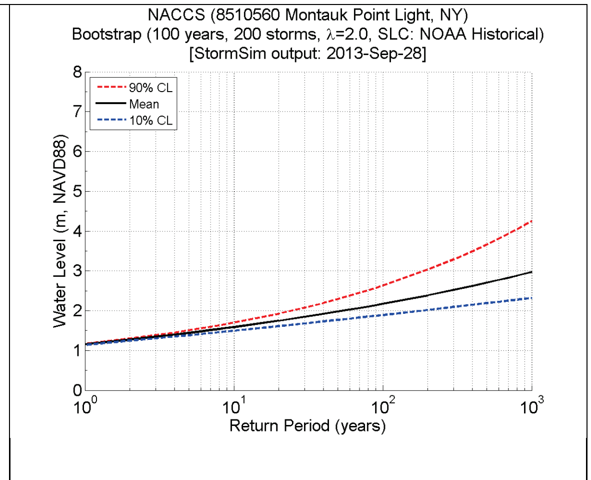


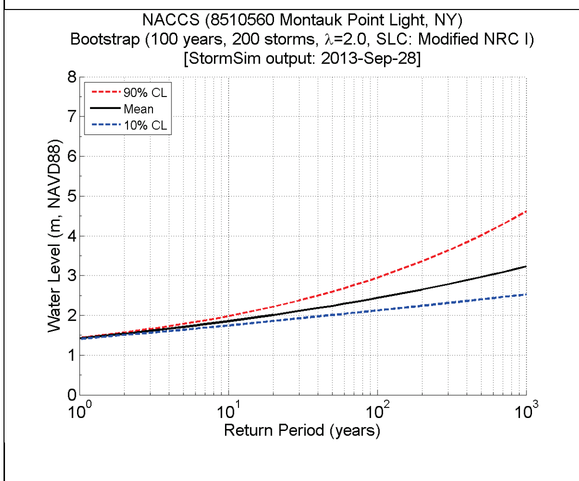
NACCS (8452660 Newport, RI)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
NACCS (8452660 Newport, RI)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
NACCS (8452660 Newport, RI)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
NACCS (8452660 Newport, RI)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
NACCS (8452660 Newport, RI)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
NACCS (8452660 Newport, RI)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
0
1
2
3
4
5
6
7
8
10^0
10^1
10^2
10^3

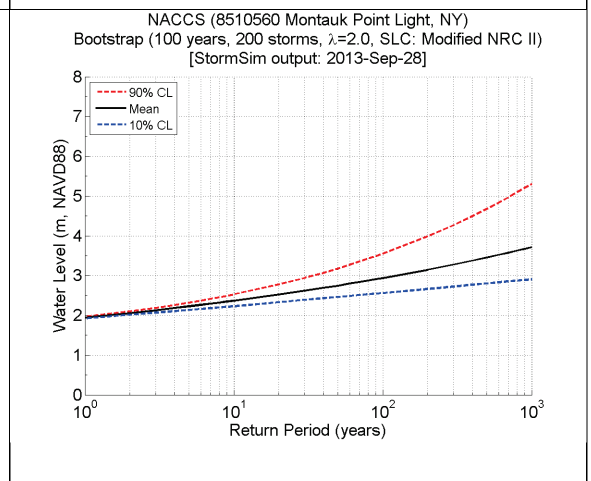

NACCS (8454000 Providence, RI)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8454000 Providence, RI)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8454000 Providence, RI)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8454000 Providence, RI)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8454000 Providence, RI)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8454000 Providence, RI)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

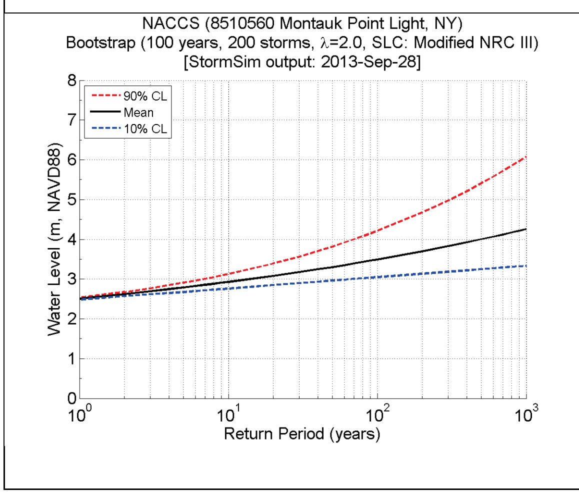

NACCS (8461490 New London, CT)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8461490 New London, CT)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8461490 New London, CT)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8461490 New London, CT)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8461490 New London, CT)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8461490 New London, CT)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

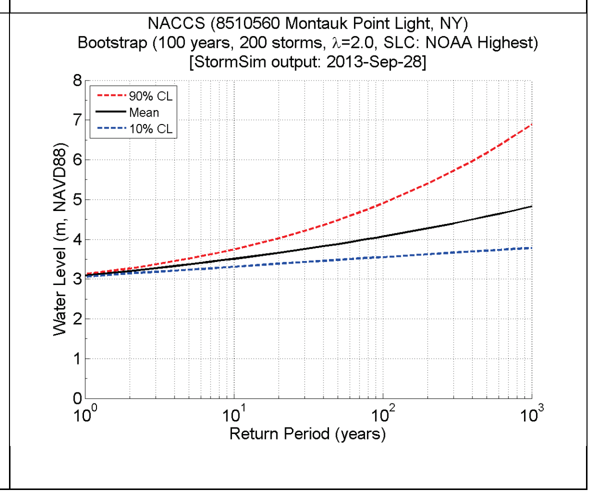

NACCS (8510560 Montauk Point Light, NY)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
0
1
2
3
4
5
6
7
8
10^0
10^1
10^2
10^3
Return Period (years)

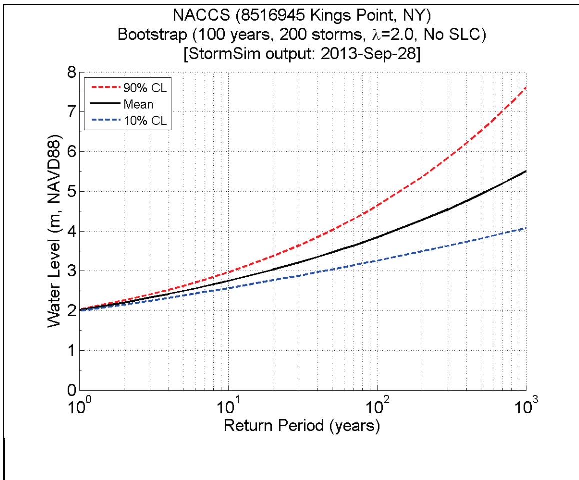

NACCS (8510560 Montauk Point Light, NY)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
0
1
2
3
4
5
6
7
8
10^0
10^1
10^2
10^3
Return Period (years)

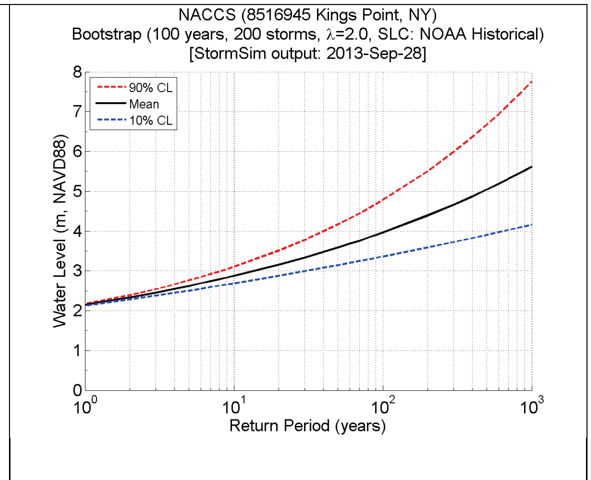

NACCS (8510560 Montauk Point Light, NY)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
0
1
2
3
4
5
6
7
8
10^0
10^1
10^2
10^3
Return Period (years)

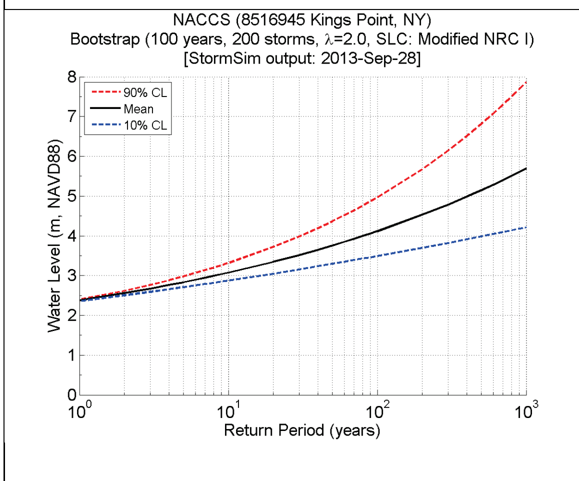

NACCS (8510560 Montauk Point Light, NY)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
0
1
2
3
4
5
6
7
8
10^0
10^1
10^2
10^3
Return Period (years)

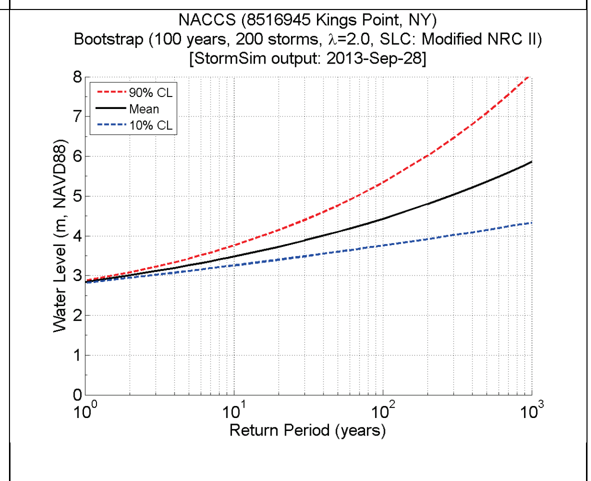

NACCS (8510560 Montauk Point Light, NY)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
0
1
2
3
4
5
6
7
8
10^0
10^1
10^2
10^3
Return Period (years)

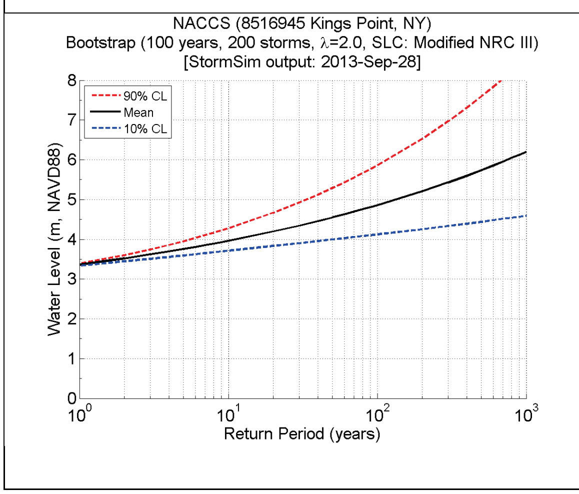

NACCS (8510560 Montauk Point Light, NY)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
0
1
2
3
4
5
6
7
8
10^0
10^1
10^2
10^3
Return Period (years)

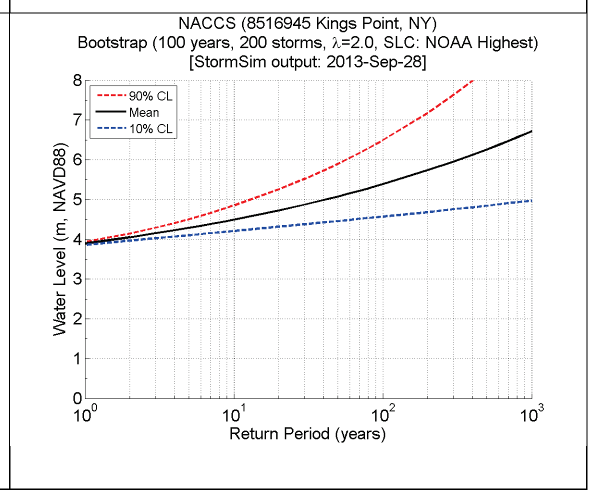

NACCS (8516945 Kings Point, NY)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

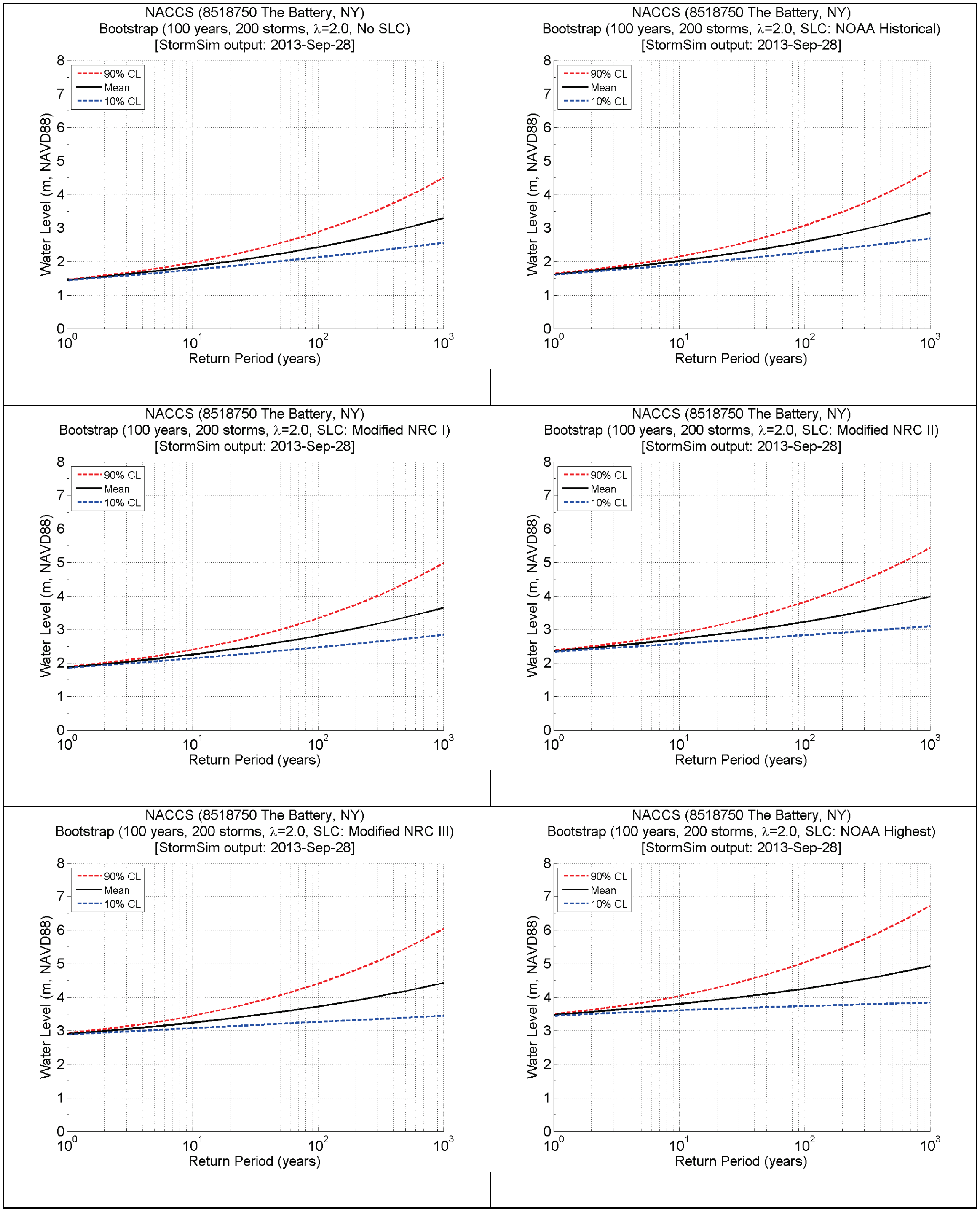

NACCS (8516945 Kings Point, NY)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

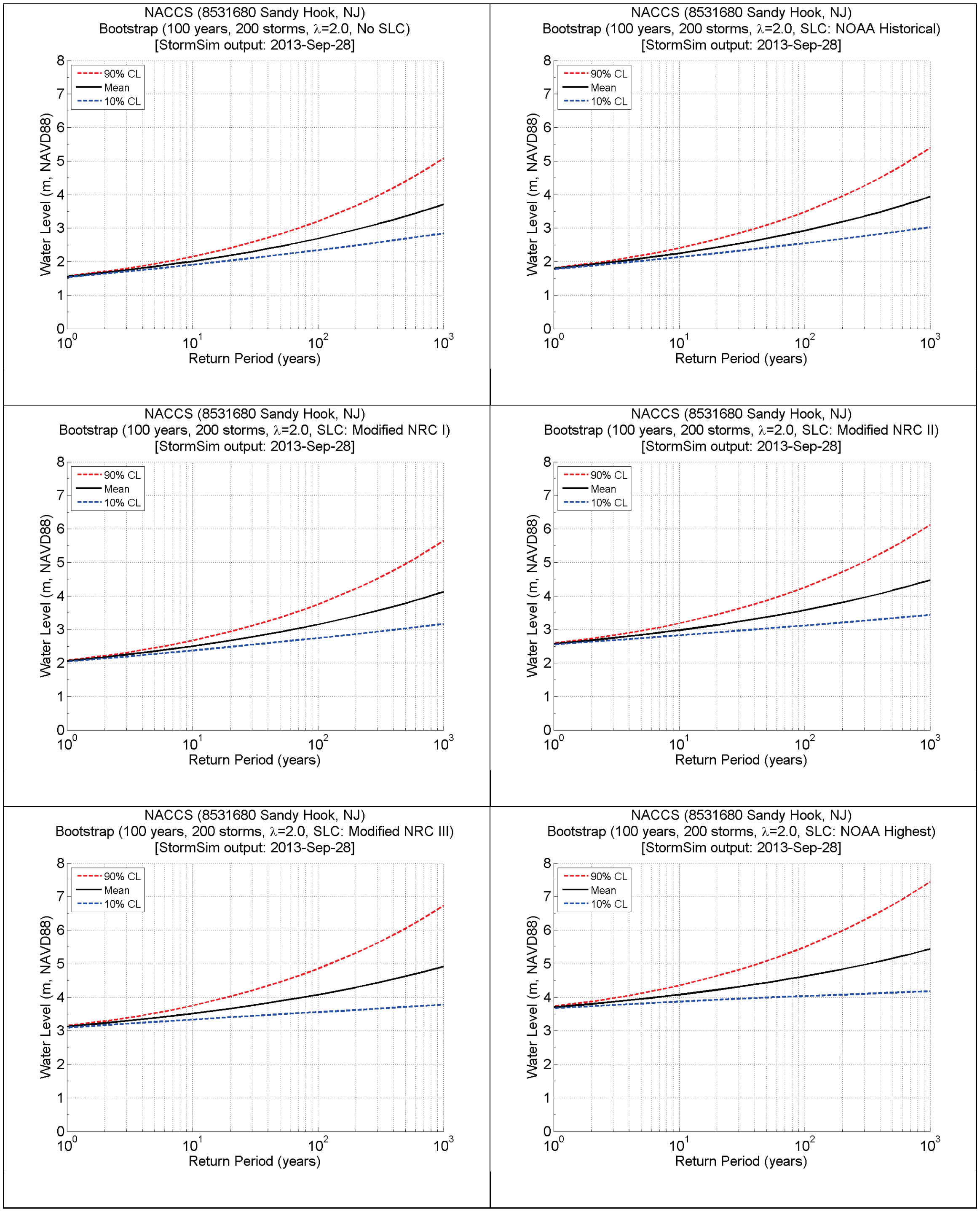

NACCS (8516945 Kings Point, NY)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

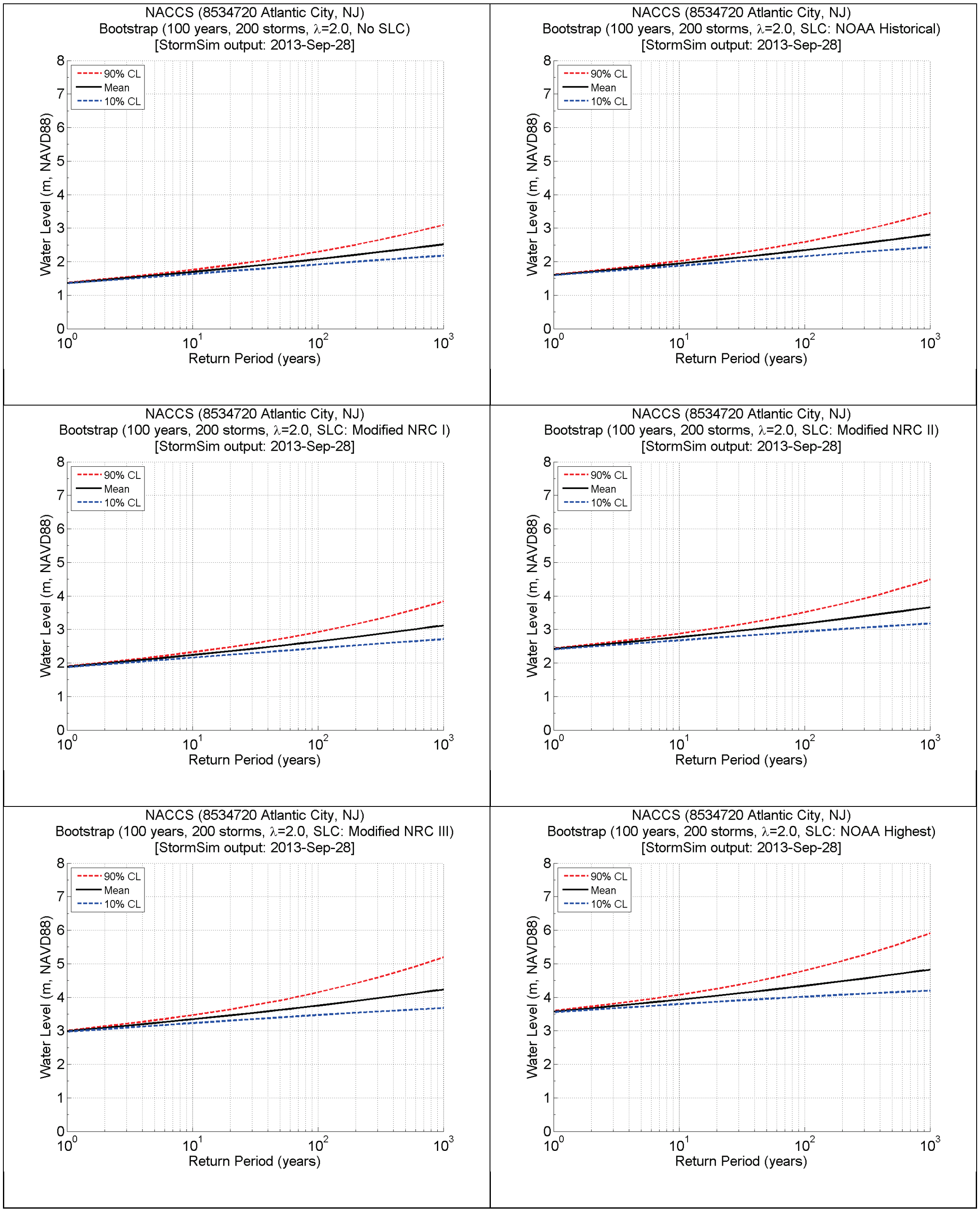

NACCS (8516945 Kings Point, NY)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

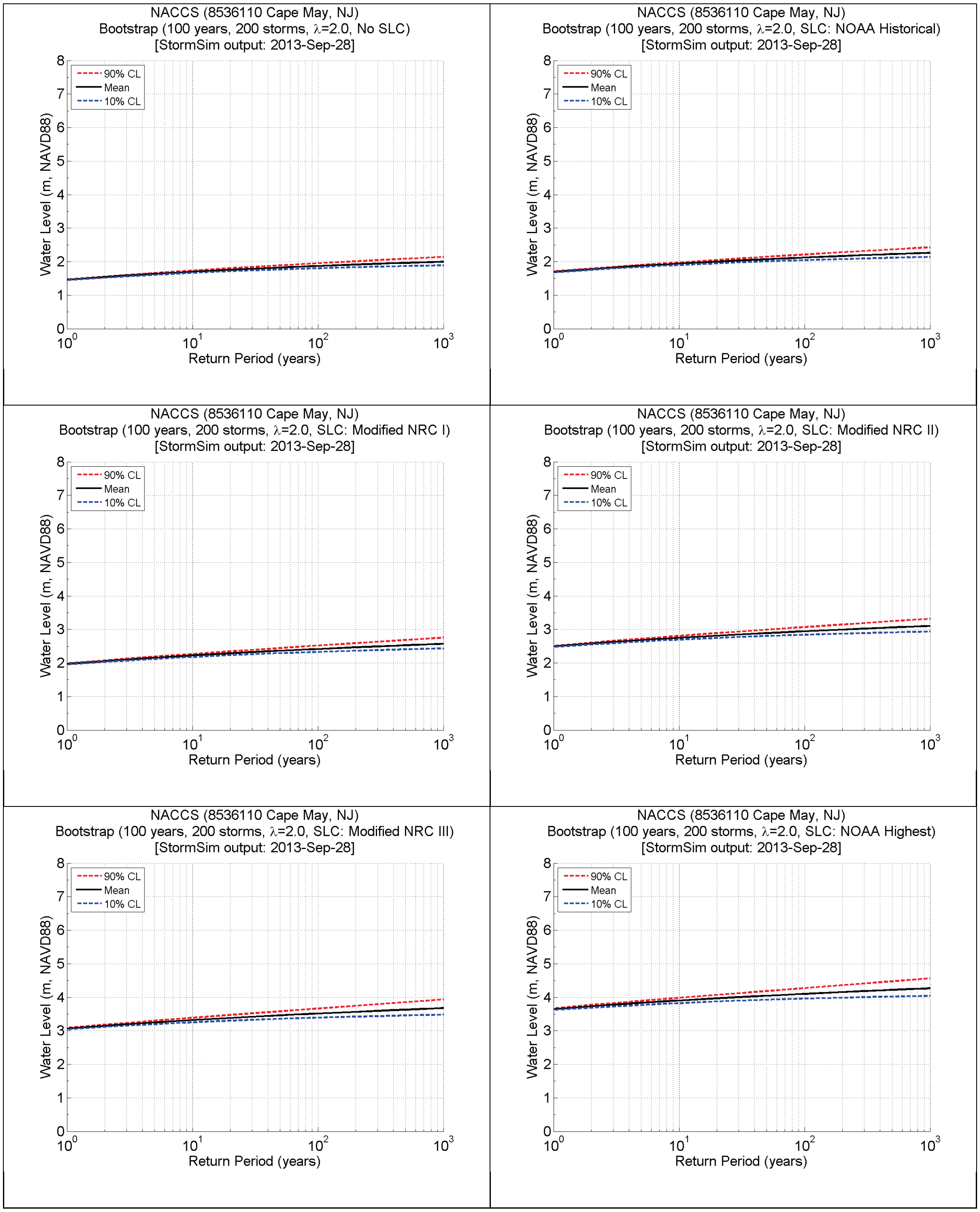

NACCS (8516945 Kings Point, NY)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

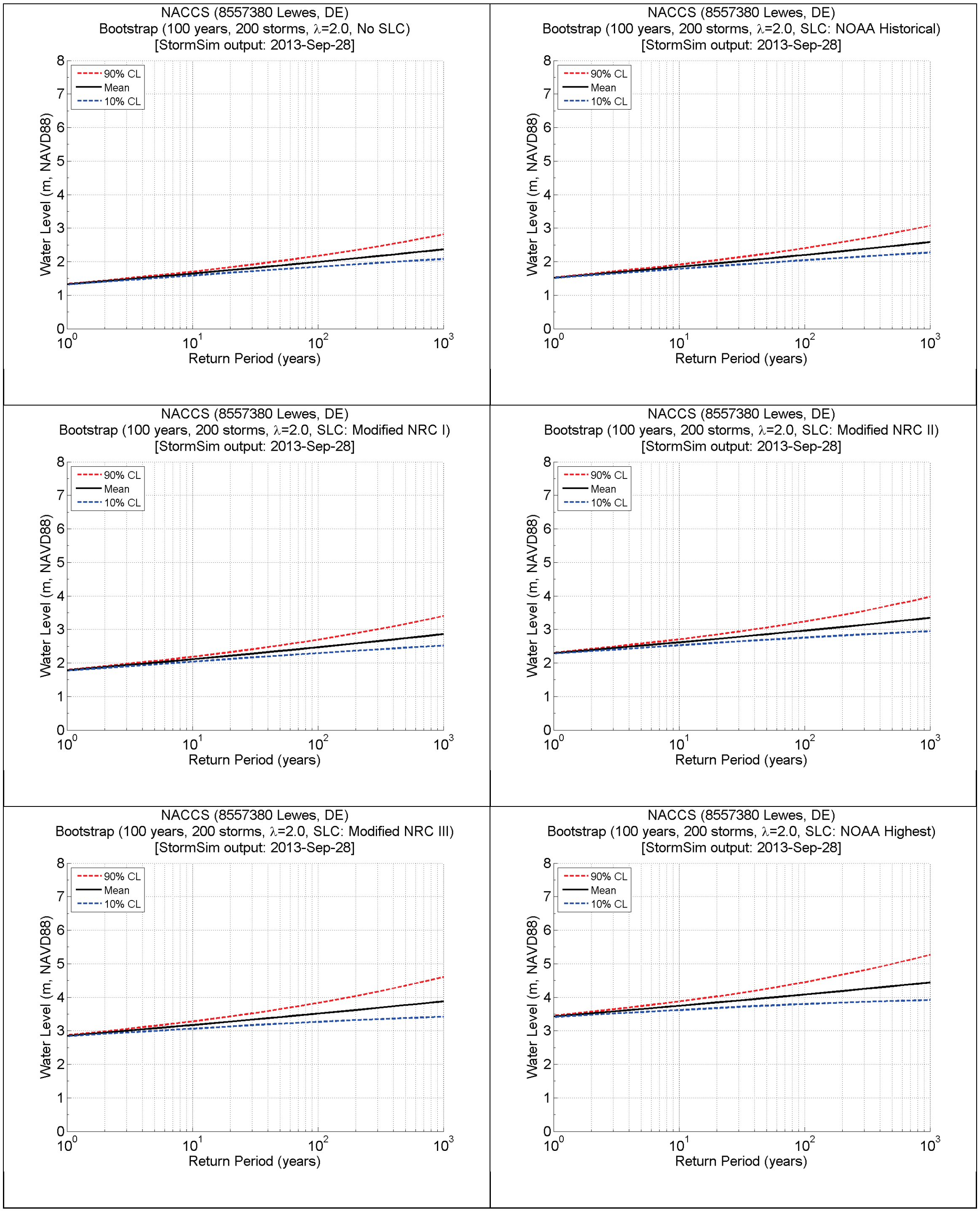

NACCS (8516945 Kings Point, NY)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

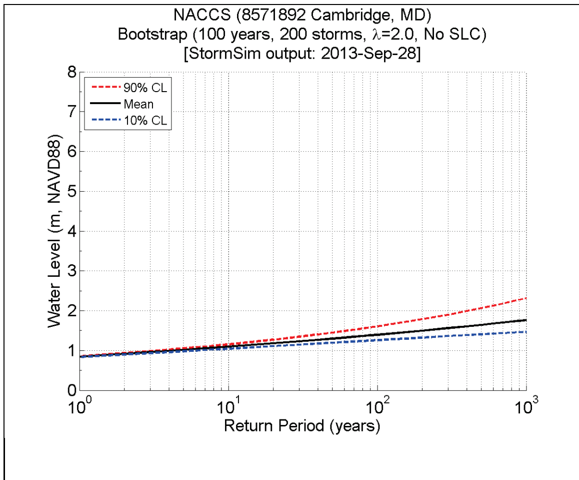

NACCS (8518750 The Battery, NY)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
NACCS (8518750 The Battery, NY)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
NACCS (8518750 The Battery, NY)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
NACCS (8518750 The Battery, NY)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
NACCS (8518750 The Battery, NY)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
NACCS (8518750 The Battery, NY)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

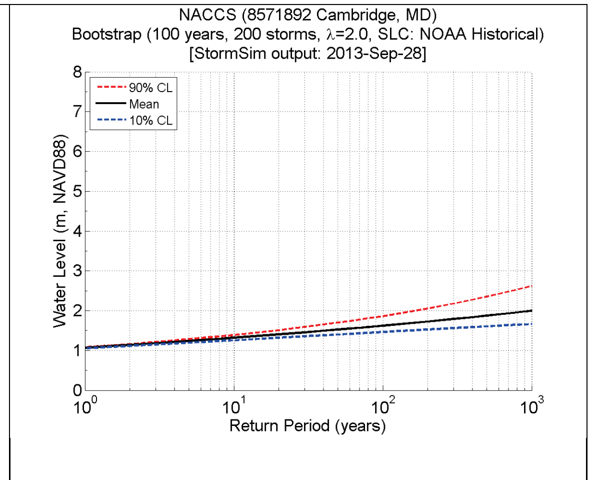

NACCS (8531680 Sandy Hook, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8531680 Sandy Hook, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
NACCS (8531680 Sandy Hook, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
NACCS (8531680 Sandy Hook, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
NACCS (8531680 Sandy Hook, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
NACCS (8531680 Sandy Hook, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]

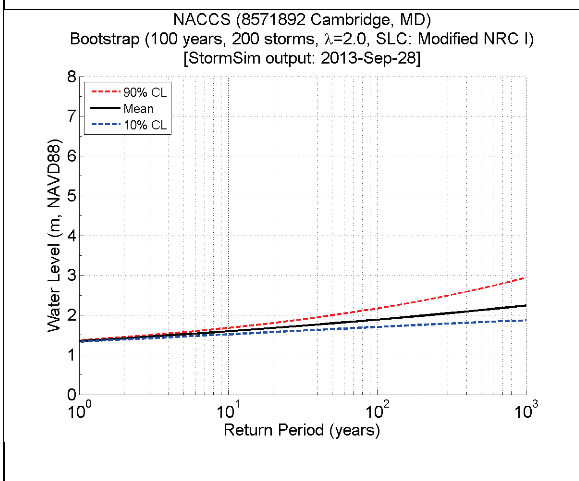

NACCS (8534720 Atlantic City, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
NACCS (8534720 Atlantic City, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
NACCS (8534720 Atlantic City, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
NACCS (8534720 Atlantic City, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
NACCS (8534720 Atlantic City, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
NACCS (8534720 Atlantic City, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
0
1
2
3
4
5
6
7
8
10^0
10^1
10^2
10^3

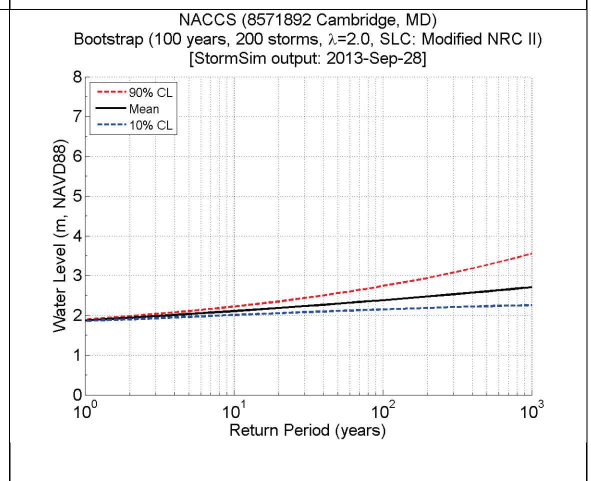

NACCS (8536110 Cape May, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8536110 Cape May, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8536110 Cape May, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8536110 Cape May, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8536110 Cape May, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8536110 Cape May, NJ)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

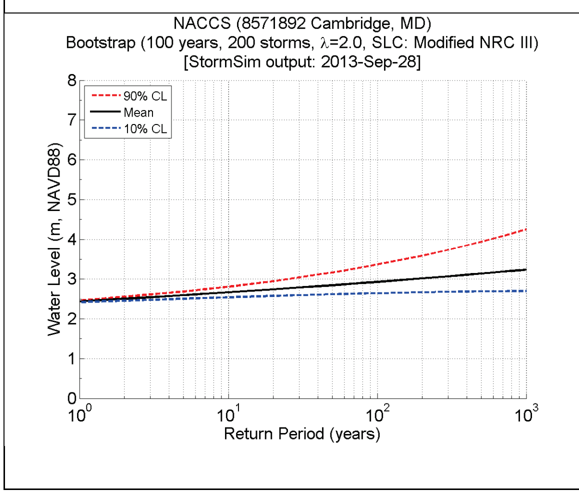

NACCS (8557380 Lewes, DE)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8557380 Lewes, DE)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
NACCS (8557380 Lewes, DE)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
NACCS (8557380 Lewes, DE)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
NACCS (8557380 Lewes, DE)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
NACCS (8557380 Lewes, DE)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]

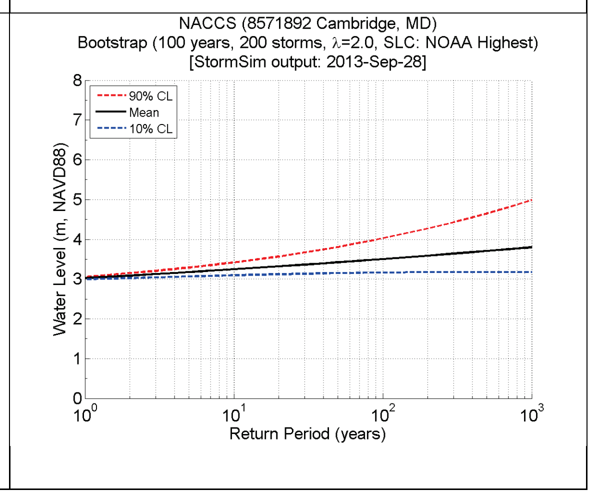

NACCS (8571892 Cambridge, MD)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

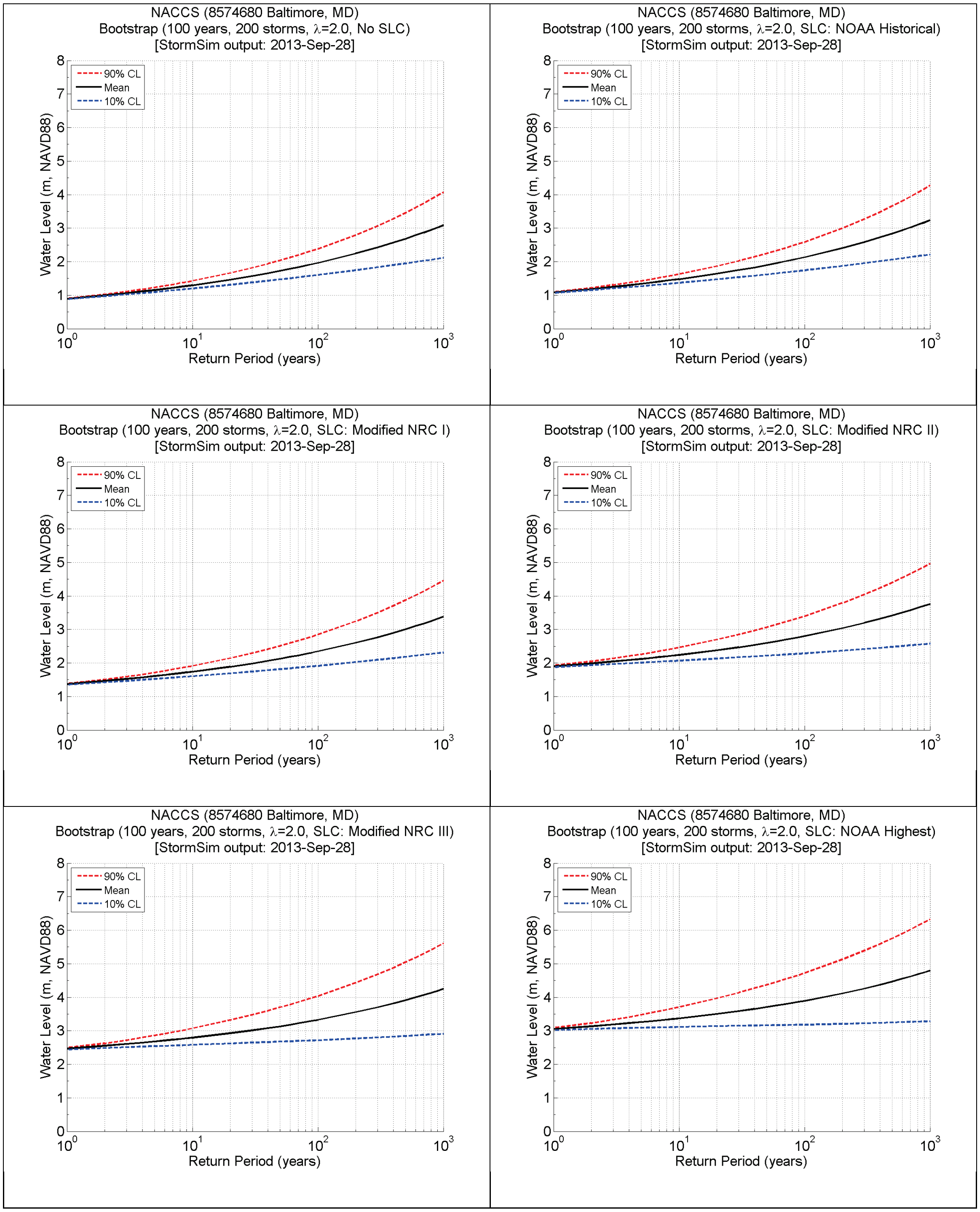

NACCS (8571892 Cambridge, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

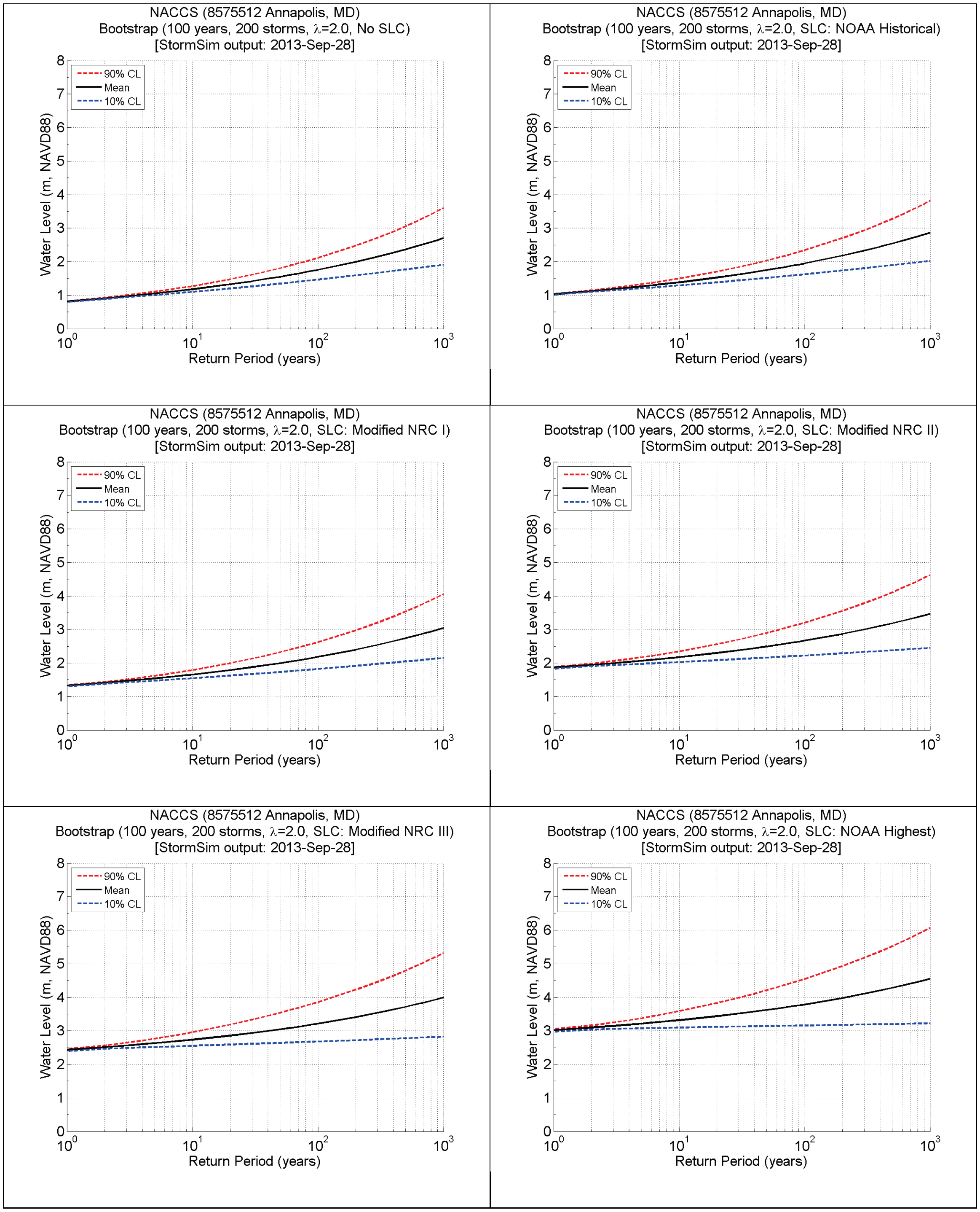

NACCS (8571892 Cambridge, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)


NACCS (8571892 Cambridge, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)


NACCS (8571892 Cambridge, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)


NACCS (8571892 Cambridge, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)


NACCS (8574680 Baltimore, MD)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
NACCS (8574680 Baltimore, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
NACCS (8574680 Baltimore, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
NACCS (8574680 Baltimore, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
NACCS (8574680 Baltimore, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
NACCS (8574680 Baltimore, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
0
1
2
3
4
5
6
7
8
10^0
10^1
10^2
10^3


NACCS (8575512 Annapolis, MD)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
NACCS (8575512 Annapolis, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
NACCS (8575512 Annapolis, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
NACCS (8575512 Annapolis, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
NACCS (8575512 Annapolis, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
NACCS (8575512 Annapolis, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
0
1
2
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4
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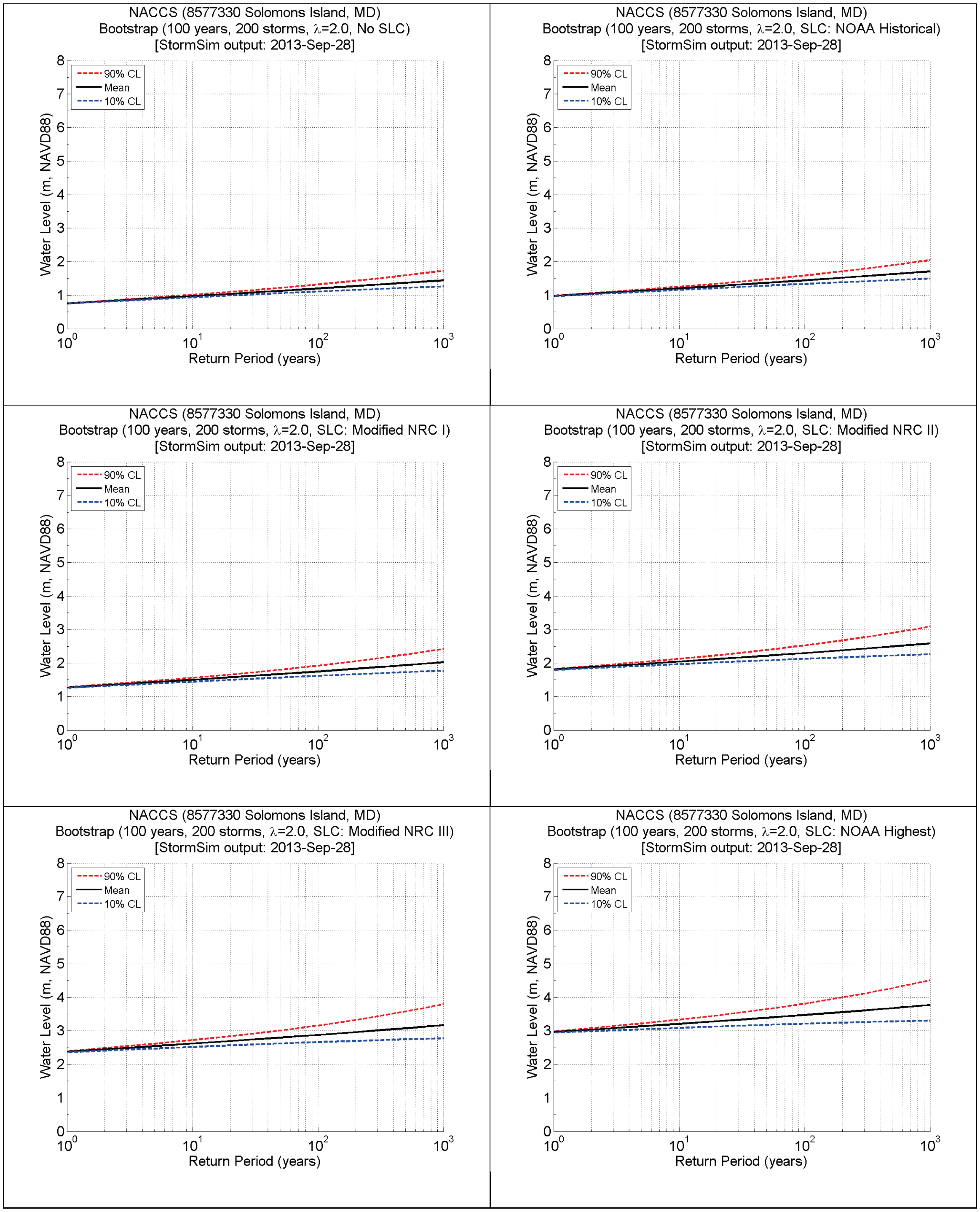
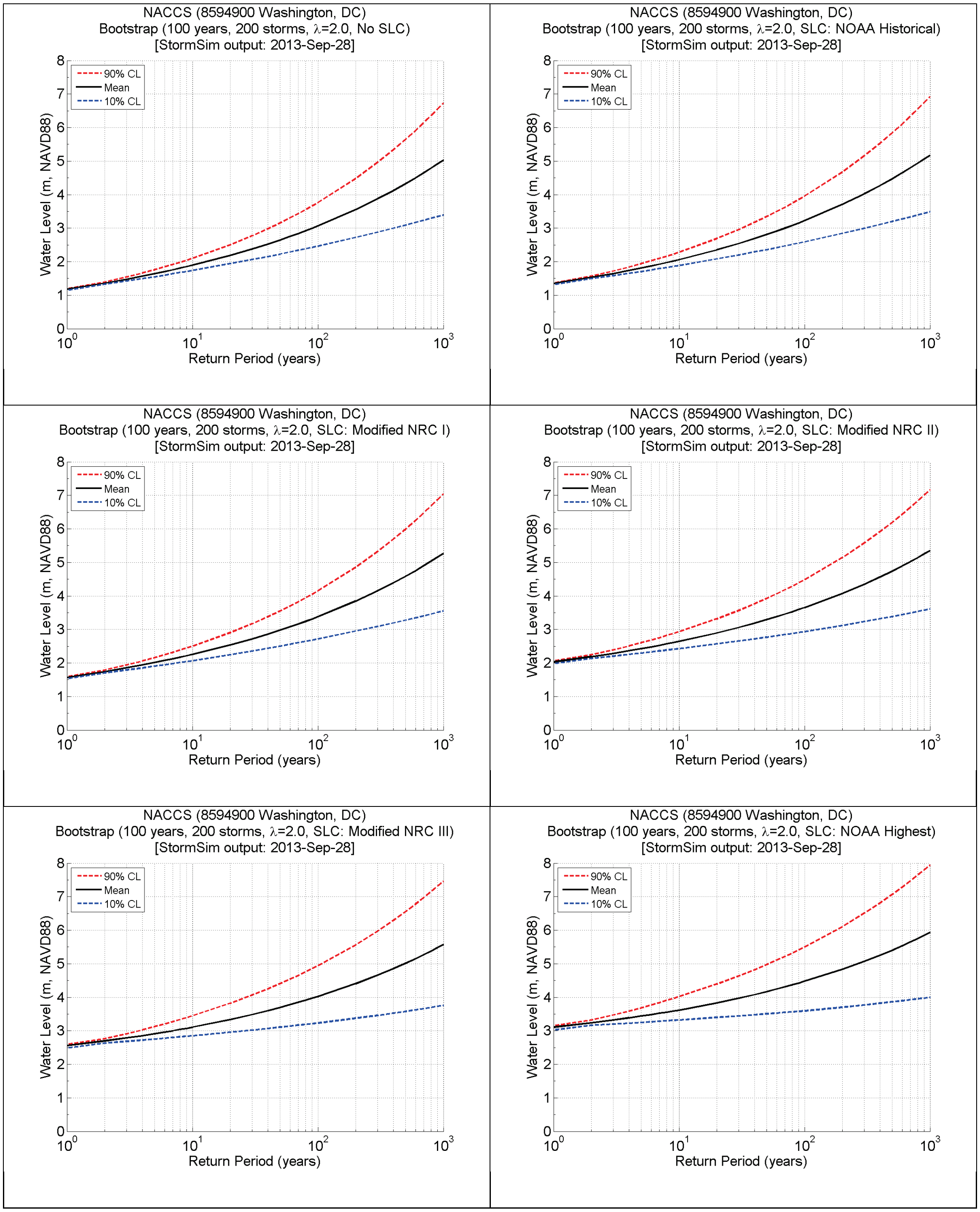
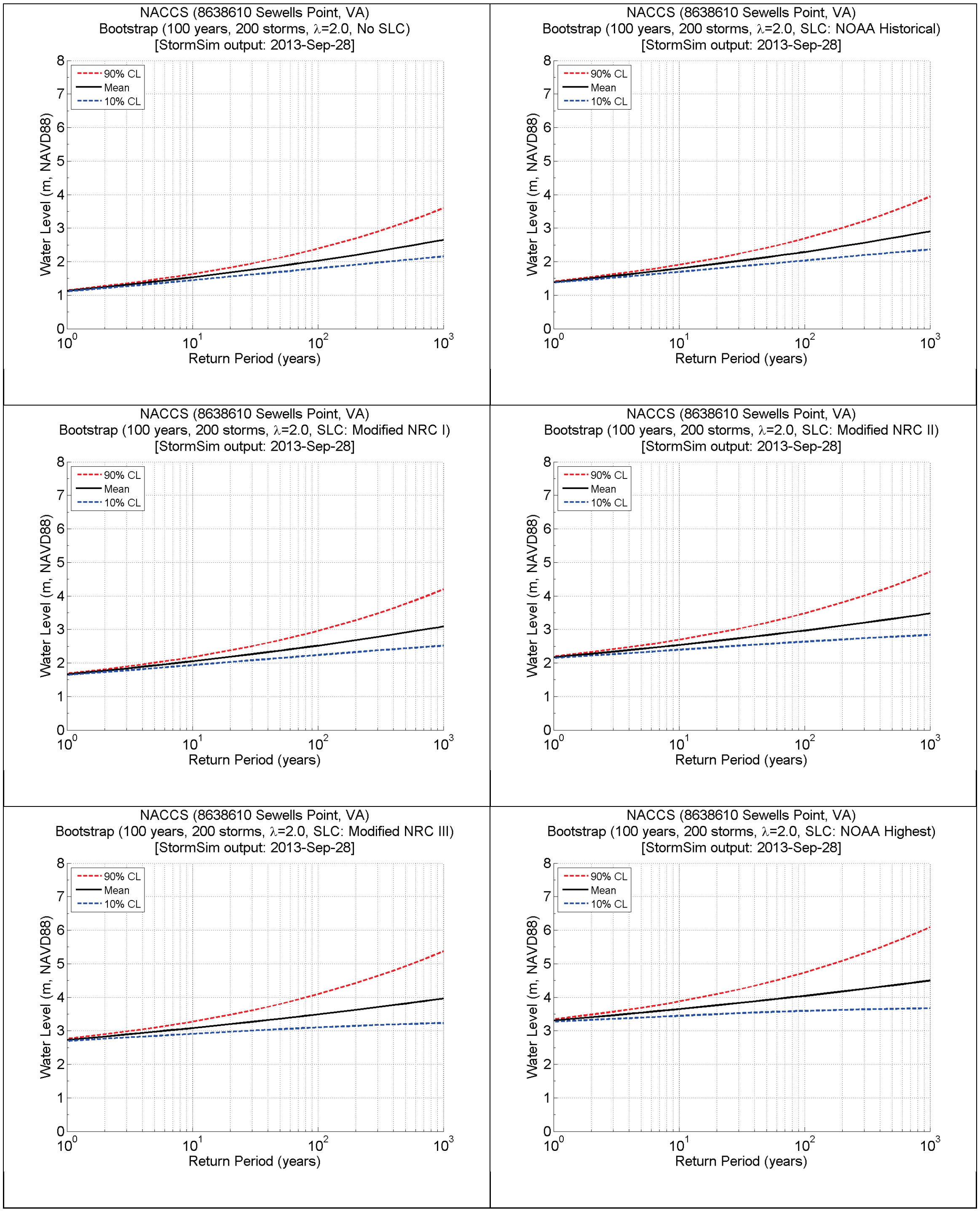
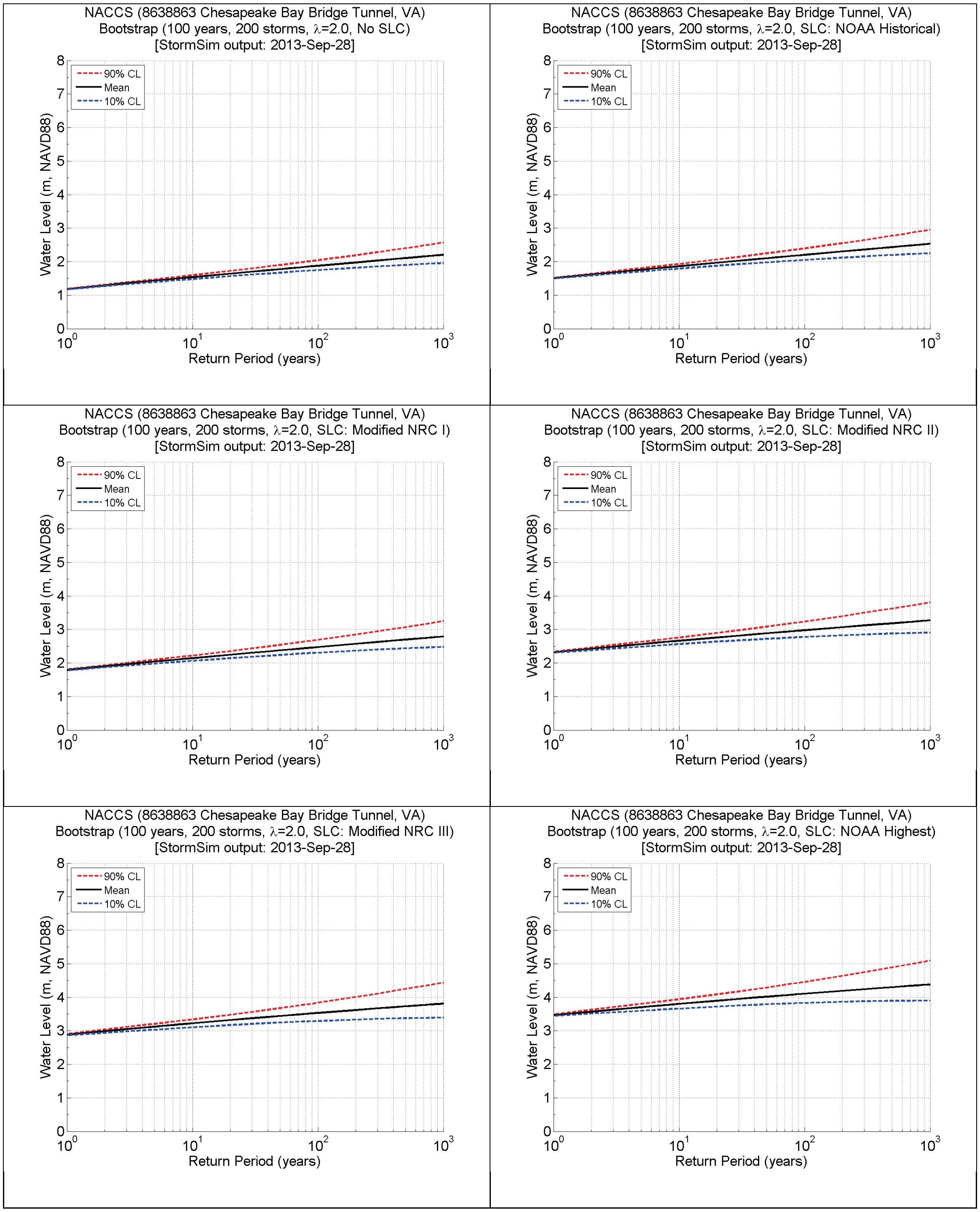
8
10^0
10^1
10^2
10^3


NACCS (8577330 Solomons Island, MD)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
NACCS (8577330 Solomons Island, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
NACCS (8577330 Solomons Island, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
NACCS (8577330 Solomons Island, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
NACCS (8577330 Solomons Island, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
NACCS (8577330 Solomons Island, MD)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
0
1
2
3
4
5
6
7
8
10^0
10^1
10^2
10^3


NACCS (8594900 Washington, DC)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8594900 Washington, DC)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8594900 Washington, DC)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8594900 Washington, DC)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8594900 Washington, DC)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8594900 Washington, DC)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)


NACCS (8638610 Sewells Point, VA)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8638610 Sewells Point, VA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8638610 Sewells Point, VA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8638610 Sewells Point, VA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8638610 Sewells Point, VA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)
NACCS (8638610 Sewells Point, VA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)


NACCS (8638863 Chesapeake Bay Bridge Tunnel, VA)
Bootstrap (100 years, 200 storms, λ=2.0, No SLC)
[StormSim output: 2013-Sep-28]
NACCS (8638863 Chesapeake Bay Bridge Tunnel, VA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Historical)
[StormSim output: 2013-Sep-28]
NACCS (8638863 Chesapeake Bay Bridge Tunnel, VA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC I)
[StormSim output: 2013-Sep-28]
NACCS (8638863 Chesapeake Bay Bridge Tunnel, VA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC II)
[StormSim output: 2013-Sep-28]
NACCS (8638863 Chesapeake Bay Bridge Tunnel, VA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: Modified NRC III)
[StormSim output: 2013-Sep-28]
NACCS (8638863 Chesapeake Bay Bridge Tunnel, VA)
Bootstrap (100 years, 200 storms, λ=2.0, SLC: NOAA Highest)
[StormSim output: 2013-Sep-28]
90% CL
Mean
10% CL
Water Level (m, NAVD88)
Return Period (years)

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Norberto C. Nadal-Caraballo and Jeffrey A. Melby

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Coastal and Hydraulics Laboratory
U.S. Army Engineer and Development Center
3090 Halls Ferry Road
Vicksburg, MS 39180-6199

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14. ABSTRACT
The U.S. North Atlantic coast is subject to coastal flooding as a result of both severe extratropical storms (e.g., Nor'easters) and tropical cyclones (hurricanes). The North Atlantic Coast Comprehensive Study (NACCS) seeks to quantify existing and future forcing for use in assessing potential engineering projects that would reduce flooding risk and increase resiliency. The study encompasses the coastal region from Virginia to Maine. Extreme water levels as a function of return period were estimated for 23 gages spanning the northeast coast region. Continuous parametric distributions as well as empirical extremal distributions were computed as part of the statistical analysis. The extreme water level results based on historical data are shown to agree well with those computed by NOAA. Return period results for a range of sea level rise scenarios are presented as mean distributions as well as 10% and 90% confidence limits. Estimates of future extreme water levels due to sea level change represent the expected levels at the end of the 100-year horizon between 2015 and 2114.

15. SUBJECT TERMS
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Monte Carlo Life-Cycle
Peaks over threshold
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